

**AN INVESTIGATION OF THE EFFECTS OF
ELECTRO-OSMOSIS ON THE
CONSOLIDATION CHARACTERISTICS
OF ILLITE**

DAVID G. TARRAN

AN INVESTIGATION ON THE EFFECTS OF
ELECTRO-OSMOSIS ON THE CONSOLIDATION
CHARACTERISTICS OF ILLITE

by

David G. Tarran

A Thesis Submitted to the Faculty
of the Department of Civil Engineering
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF CIVIL ENGINEERING

TABLE OF CONTENTS

	Page
LIST OF TABLES	v
LIST OF FIGURES	vi
FOREWORD	ix
ABSTRACT	x
I. INTRODUCTION	1
A. Historical Review	1
B. Statement of the Problem	7
II. THEORY	9
A. Definition of Consolidation	9
B. Discussion of the Electro-osmotic Phenomenon	10
C. General Effects of Electro-osmosis on Soil-Water Systems	16
III. MATERIALS AND APPARATUS	24
A. Design	24
B. Assembly	37
C. Calibration	38
D. Soil Sample Description	41
IV. PROCEDURE	47
A. Sample Preparation	47
B. Assembly of Apparatus	49
C. General Testing Procedure	53
V. RESULTS AND DISCUSSION	58
A. General	58
1. Water Content Changes	59
2. Atterberg Limit Value Changes	61
3. Physical Appearance	62
4. Expansion Effects	64
5. Electrical Current and Voltage Changes	64
6. Temperature Differentials	67
7. Anode Decomposition	69
8. pH Values	69
9. Changes in Sample Content	70

V. RESULTS AND DISCUSSION (Con't.)

B. Test Number 1	75
C. Test Number 2	83
D. Tests Numbers 3 and 4	91
E. Test Number 5	91
F. Test Number 6	98

VI. CONCLUSIONS 110

VII. RECOMMENDATIONS 113

VIII. BIBLIOGRAPHY 117

LIST OF TABLES

	Page
Table 1 Atterberg Limits	60
Table 2 Water Contents	60
Table 3 Duration in Minutes for each Phase of Tests Conducted	63

LIST OF FIGURES

		Page
Figure I	Comparison of Flow in a single Capillary Tube.	14
Figure II	Electro-Osmotic Flow in a Capillary Tube.	14
Figure III	A Space Lattice Structure	17
Figure IV	Side and Top Views of Electro-Osmometer	25
Figure V	Schematic Diagram of Electro-Osmometer.	26
Figure VI	View of Left End Plate Assembly and Sample Holder	31
Figure VII	View of Right End Plate Assembly. . . .	31
Figure VIII	View of Standard Consolidometer	36
Figure IX	View Showing Detail of Loading Ring Support	40
Figure X	View of Calibration Setup	40
Figure XI	Calibration Curve for Electro-Osmometer Loading Arm	42
Figure XII	Grain Size Distribution Curve	45
Figure XIII	Pre-Loading Apparatus	50
Figure XIV	General Testing Procedure	54
Figure XV	Time Versus Current Curves	65
Figure XVI	X-ray Spectrometer Trace for Untreated Sample, Test Number 2	71
Figure XVII	X-ray Spectrometer Trace for Treated Sample, Anode, Test Number 2. .	72
Figure XVIII	X-ray Spectrometer Trace for Treated Sample, Middle, Test Number 2 .	73
Figure XIX	X-ray Spectrometer Trace for Treated Sample, Cathode, Test Number 2.	74

	Page
Figure XX	Compression Versus Time Curves for 1/4 ton load increment, Sample Number 1 . . 76
Figure XXI	Compression Versus Time Curves for 1/2 ton load increment, Sample Number 1 . . 77
Figure XXII	Compression Versus Time Curves for 1 ton load increment, Sample Number 1 . . . 78
Figure XXIII	Compression Versus Time Curves for 2 ton load increment, Sample Number 1 . . . 79
Figure XXIV	Compression Versus Time Curves for 4 ton load increment, Sample Number 1 . . . 80
Figure XXV	Void Ratio Versus Load Curves for Sample Number 1 82
Figure XXVI	Compression Versus Time Curves for 1/4 ton load increment, Sample Number 2 . . 84
Figure XXVII	Compression Versus Time Curves for 1/2 ton load increment, Sample Number 2 . . 85
Figure XXVIII	Compression Versus Time Curves for 1 ton load increment, Sample Number 2 . . . 86
Figure XXIX	Compression Versus Time Curves for 2 ton load increment, Sample Number 2 . . . 87
Figure XXX	Compression Versus Time Curves for 4 ton load increment, Sample Number 2 . . . 88
Figure XXXI	Void Ratio Versus Load Curves for Sample Number 2 90
Figure XXXII	Compression Versus Time Curves for Sample Numbers 3 and 4 92
Figure XXXIII	Compression Versus Time Curves for 1/4 ton load increment, Sample Number 5 . . 93
Figure XXXIV	Compression Versus Time Curves for 1/2 ton load increment, Sample Number 5 . . 94
Figure XXXV	Compression Versus Time Curves for 1 ton load increment, Sample Number 5 . . . 95

	Page
Figure XXXVI Compression Versus Time Curves for 2 ton load increment, Sample Number 5 .	96
Figure XXXVII Compression Versus Time Curves for 4 ton load increment, Sample Number 5 .	97
Figure XXXVIII Void Ratio Versus Load Curves for Sample Number 5	99
Figure XXXIX Compression Versus Time Curves for 1/4 ton load increment, Sample Number 6.	100
Figure XXXX Compression Versus Time Curves for 1/2 ton load increment, Sample Number 6.	101
Figure XXXXI Compression Versus Time Curves for 1 ton load increment, Sample Number 6 .	102
Figure XXXXII Compression Versus Time Curves for 2 ton load increment, Sample Number 6 .	103
Figure XXXXIII Compression Versus Time Curves for 4 ton load increment, Sample Number 6 .	104
Figure XXXXIV Void Ratio Versus Load Curves for Sample Number 6	106
Figure XXXXV Coefficient of Consolidation Versus Load Curves for Sample Numbers 1 and 2.	107
Figure XXXXVI Coefficient of Consolidation Versus Load Curves for Sample Numbers 5 and 6.	108

FOREWORD

The author wishes to extend his sincere appreciation and gratitude to his faculty advisor, Professor E. J. Kilcawley, Head of the Division of Soil Mechanics and Sanitary Engineering, Department of Civil Engineering, Rensselaer Polytechnic Institute for allowing the author considerable freedom of decision and latitude of subject in conducting this investigation and for the fine comprehensive background material presented in the classroom.

To Professor S.V. Best, the author wishes to express his sincere appreciation for the assistance furnished during the design of electro-osmometer and for the valuable suggestions given during the entire investigation.

To Assistant Professor J.E. Munzer and Assistant Professor W. Kelleher, the author wishes to express his appreciation for the many helpful suggestions and hints given during the investigation.

To C.C. Heid Jr., and J.E. Powell the author wishes to express his gratitude for the invaluable assistance they rendered in conducting Differential Thermal analysis and X-ray Diffraction analysis respectively on soil samples used in the investigation.

And to Bernard E. Butler, Instructor in the Civil Engineering Department, the author gives deep thanks for his advice and help in all phases of the investigation.

ABSTRACT

Six series of tests were conducted on Morris, Illinois illite samples to determine the effect of the electro-osmotic phenomenon on its consolidation characteristics. In order to conduct this investigation, an electro-osmometer was designed, constructed and calibrated. The general theme of this investigation was a comparison of the consolidation characteristics of two identical soil samples which were subjected to two different types of consolidation procedure. One sample was consolidated under increasing load increments in a standard consolidometer and the other was subjected to identical load increments plus an electrical potential in an electro-osmometer.

Illite soils when subjected to electro-osmotic treatment tend toward structural changes and characteristic changes in Atterberg limit values. The liquid limit, plastic limit and plasticity index values of an illite subjected to an electrical potential are somewhat higher than those values derived from the untreated samples.

The illite soils subjected to electrical potential do not reach as low a void ratio value as those of the untreated illites for the same load increment. Results of this investigation indicate that the above mentioned condition is probably due to the effect of electro-chemical hardening which is an accompanying effect of electro-osmosis.

Generally speaking an illite sample subjected to

an electrical potential has a faster rate of consolidation than that of the untreated sample. However, as the duration of the application of electrical potential and the magnitude of the load increment increases the differential consolidation rate is decreased.

This investigation also indicated that an increase in the duration of the application of electrical potential prior to loading resulted in a more rapid development of near-maximum sample resistance to electric current flow.

Determinations of coefficients of consolidation, pH values for the liquid in the electro-osmometer, anode plate decomposition and before and after electrical treatment water content values were also made.

PART I.
INTRODUCTION

A. Historical Review

The importance of soil as an engineering material began to manifest itself when primitive man realized that more comfort and utility could be derived from a structure appropriately designed and constructed than from those that he might accidentally discover existing in nature. As he attempted to construct his first primitive structure the enigmatic problems contained in the field of soil mechanics and foundation engineering rose but were usually circumvented by the flexibility of the location of his structure.

As civilization progressed man's structural handiwork became larger and more complex and the location of his structures were effected by social, religious, political and economical factors all of which deprived him the flexibility and freedom of location he had once enjoyed. Scientific discoveries and new construction techniques allowed him to build great awe-inspiring structures but oddly enough comparatively little scientific investigation and analysis were actually accomplished for the soil on which these structures were to be placed. This phase of the construction process was perplexing and exceedingly difficult to evaluate and was regarded by the engineer as a portion of the work that could best be handled in the

field by men of great experience and "know how".

In recent years foundation problems have been forcibly brought to the attention of engineers by structural failures attributed only to poor foundation conditions. Economy has been a factor that has demanded the knowledge of soil behavior if the foundations for these structures were to be placed with a minimum usage of money, material and labor.

Probably one of the most costly operations in foundation construction is the unwatering of a construction area in order that the work might be accomplished safely and in the dry. Various methods of accomplishing this result such as cofferdams, caissons, the Joosten method, freezing, grouting, well points, etc., have been developed.

Such methods as the use of cofferdams and caissons are extremely effective but are inherently expensive. Methods such as the Joosten method, freezing, grouting and the use of well points are excellent under ideal conditions but most of them are not particularly effective or practical in soils which contain grain sizes that are as small and as active as those of various clays.

In the recent years a process known as electro-osmosis has given the foundation engineers hope that a simple and inexpensive solution to the problem indicated above exists.

Electro-osmosis had a slow painful development fraught with the inability of the scientists and investigators to explain the phenomenon that occurred when an electrical potential was applied to a soil-water system. Even in present times the phenomenon is not well understood and many investigators have developed their pet theories to explain it.

In the beginning the author will consider the general phenomenon of electro-osmosis until that historical period is reached when diversified investigations into the many aspects of electro-osmosis began and then specific historical consideration of the effects of electrical current on the consolidation of clays will be treated.

Electro-osmosis probably had its beginning in 1807 when Reuss discovered that water would flow through a porous diaphragm when an electric current was applied to the system.

In 1861 Quinche inferred that a double layer similar to that proposed by Helmholtz existed and that it depended on the supposition that spontaneous electrification existed at the contact surface of a solid and a liquid prior to any external electrical action (9).

Perhaps one of the most significant contributions explaining the theory of electro-osmosis was the interpretation proposed by Helmholtz in 1877 known as the

"Double Layer" hypothesis. It seems to put into words Quinche's idea. However, Helmholtz's theory is considerably different than that of Quinche and his explanation of the electro-osmotic phenomenon is so outstanding that he is given credit for its origin. Although many physicists and scientists have disagreed with portions of the theory it is considered sound, plausible and useful. His hypothesis will be discussed in some detail in the "Theory Section" of this thesis.

The Helmholtz hypothesis was subsequently modified by Lamb, Smoluchowski, Perrin and others but the quantitative results remained substantially unchanged.

From the late 1920's to the present a host of scientific investigators have been at work not only trying to find practical application of the phenomenon of electro-osmosis in soils but also trying to find the answers to a myriad of questions concerning the theoretical properties of the electro-osmotic phenomenon in soils. Although each has made a worthwhile contribution toward the understanding of the subject much investigation still remains before complete enlightenment can be obtained. Although all of these investigator's contributions are indirectly related to the author's thesis only those dealing with the specific problem of the effects of electro-osmosis on the consolidation of soil will be mentioned.

Dr. Leo Casagrande (16) has been a constant contributor not only from the practical application aspects of the problem but also in the field of better understanding of the phenomenon of electro-osmosis. In 1934 he discovered that by using aluminum anodes instead of other metals, clay soils are stabilized and hardened irreversibly. This discovery was a great boon to the practical application of electro-osmosis.

In 1936 Endell and Hoffman (7) discovered that Atterberg's liquid limit and the angle of internal friction are increased when a soil is subjected to electrical treatment. These investigators made some very astute observations concerning the hardening of clays subjected to electric potential. These observations will be discussed in detail in the "Theory Section" of this thesis because they will be invaluable in explaining the results of the author's investigation.

Probably the first investigator to study the electro-chemical consolidation of soils was W. Bernatzik (2), who in 1939 constructed a combined ring-shear and consolidation of clay specimens before and after electrical treatment. He showed that the treated specimen had an increased value of the angle of internal friction which was probably due to electro-chemical hardening.

In 1937, Schaad and Haefeli (8) designed an electro-osmometer similar to the one designed by the author

and Butler for the determination of electrical potential on permeability and consolidation of clayey silts.

Edmund Preece (11) produced a monumental paper in 1947 that seemed to gather up the loose ends concerning the phenomenon of electro-osmosis and record all the pertinent facts, theories and experimental results that have been promulgated up to the time the paper was issued in a clear concise systematic manner. It is not a summary of each investigator's work but is an attempt to provide a semblance of continuity in the development of the explanation of the electro-osmotic phenomenon.

Dawson and McDonald (6) in 1948 made a number of tests by use of a standard type of consolidation apparatus. They determined that the liquid limit, plastic limit, plasticity index and shrinkage limit were decreased after electrical treatment. They also conducted tests using alternating current but concluded that the resulting consolidation effect was due to the resistance heating of the clay. Poisson (5) argued that alternating current tended only to cause an increase in water content of the clay. This comparison merely indicates the range of results that were obtained for similar tests.

Vey (18) in 1949 determined that the degree and rate of consolidation of fine-grained soils are both greatly increased by the application of an electrical potential. He indicated that electro-osmotic pressure can be represented as an increased consolidation load in the consolidation

theory. He discovered that effective consolidation of soils by electro-osmosis can be fully achieved only when used in conjunction with small external loads.

The above presentation only mentions but a few of the many contributors to the ever growing field of electro-osmosis and its application to soils. Such a brief historical resume cannot possibly do justice to the outstanding contributions of the many investigators that have come to the fore in the past twenty years. As indicated before only those authors whose conclusions were directly pertinent to the discussion of the theory of the consolidation phase of electro-osmosis were considered in this thesis.

B. Statement of the Problem

As the title of this thesis indicates the problem is to determine the effects of electro-osmosis on the consolidation characteristics of illites.

Inasmuch as equipment was not available to accomplish the above indicated task, the problem immediately increased enormously in scope to include the design and construction of an electro-osmometer. After this task was accomplished there was the problem of calibration and those necessary modifications required by inherent difficulties usually encountered in a newly designed apparatus.

After the apparatus was completed the problem evolved itself to a comparison of consolidation effects on identical samples in a standard consolidometer and the electro-osmometer. It was necessary to consolidate the sample under varying load increments in order to determine relative consolidation times. Further comparisons would be necessary in the form of void ratio versus pressure curves to determine which sample was being consolidated the most under a particular load increment. Comparison of the coefficients of consolidation was also necessary.

In order that effects of electrical current on consolidation might be considered from all points of view, it was necessary to determine changes in soil characteristics as determined by comparison of Atterberg's limits, water contents and physical appearance.

"Before and After" X-ray diffraction analysis was necessary to determine changes in crystal structure and sample content.

As is true with most research work, difficulty was encountered in checking the results obtained which was due to the fact that there were as many answers to some problems as there were investigators and to other problems there were no answers.

PART II.

THEORY

A. Consolidation

Since soil is a three phase system, i.e., a skeleton of solid grains enclosing voids which may be filled with gas or liquid or a combination of both, the decrease of the volume of a soil sample subjected to stress can be attributed to any or all of the following factors: (1) compression of the solid matter, (2) compression of water and air within the voids and (3) escape of water and air from the voids (17). For all practical purposes if the sample is completely saturated, the decrease in volume can be attributed to an escape of water from the void spaces.

Consolidation can be defined as a gradual process which involves a slow escape of water from the void system and a gradual compression of the soil mass. During the consolidation process, stress transfer is also occurring. Stress transfer takes place during the drainage process when the neutral stresses are transferred to the soil grains as intergranular stresses. The rate and amount of consolidation of a soil sample is a direct function of the rate and amount of water discharged from the sample.

Since the author's investigation deals primarily with the effects of electrical potential on the flow of water from a sample, a detailed discussion will not be presented on the theory of one-dimensional consolidation. If the reader is interested in further detail on this subject his attention is directed to Taylor's treatment of the subject (17).

In view of the above statement the remainder of the discussion on the theory involved in this thesis will be devoted exclusively to electro-osmosis and its effects on a soil-water system.

B. Discussion of the Electro-osmotic Phenomenon

Electro-osmosis is a phenomenon which occurs in a soil-water mixture when it is subjected to an electrical potential. It is defined by Vey (18) as "fundamentally a phenomenon of colloid and capillary chemistry". There are actually two phenomena which could occur in a soil-water mixture. One phenomenon occurs when an electrical potential is applied to a system wherein solid particles of colloidal size are suspended in a liquid. In this case the solid particles would move toward the poles. This phenomenon is called electrophoresis. On the other hand, if the mixture was predominately solid particles the liquid would move toward one of the poles where an electrical current was employed. This phenomenon is known as electro-osmosis.

Electro-osmosis should not be confused with osmosis because they are two distinct phenomena. Preece (11) explains osmosis as indicated in the following summary. If two solutions of different concentration are separated by an acceptable semi-permanent membrane, the molecules of the solvent, but not those of the solute will tend to pass through the membrane from the solution of the lower to that of the higher concentration. Since electro-osmosis deals primarily with the flow of the solute, the difference can be easily seen.

Karpoff (9) states that electro-osmotic flow through a soil depends upon two general factors: (1) the properties of the soil and liquid, viscosity and dielectric constant, and (2) the properties of the electrodes, i.e., the composition, conductivity, dimensions and spacing".

The theory of electro-osmosis can probably best be explained by approaching it through Helmholtz's hypothesis. Helmholtz (4) suggested that the film of water is bound to a capillary surface by means of electrostatic forces and is composed of two layers. The layer adjacent to the capillary surface is a thin dense layer of oriented water molecules and the other layer is a diffuse layer of oscillating water molecules held with less attraction than the inner layer. The inner layer is usually negatively charged while the diffuse outer layer contains a

predominance of positive charges. The application of an electrical potential will cause the water in the diffuse layer to migrate toward the cathode. The movement of this layer tends to drag the free water in the capillary tube with it.

The diffuse layer is relatively thick and materially increases the amount of water movement within the capillary tube over that occurring in a capillary tube where the free water alone moves. The above discussion is clarified by study of the graphical representation shown in Figure (I).

Helmholtz introduced a factor called the electrokinetic or Zeta potential and identified it as the potential across the double layer. He visualized the double layer as a condenser and that the Zeta potential is that portion of the potential drop that exists between the boundary separating the rigid and diffuse layers and the outer limit of the diffuse layers. Zeta potential depends quantitatively upon the total potential, the thickness of the absorbed layer and thickness of the diffused layer. The total potential will in turn depend upon the character of the solid and the solution with which it is in contact. The thickness of the absorbed layer depends on the absorbed ions, strength of the electrostatic force, the amount of absorbed water, and concentrations of ions. Any increase in the number of ions in the diffuse layer will

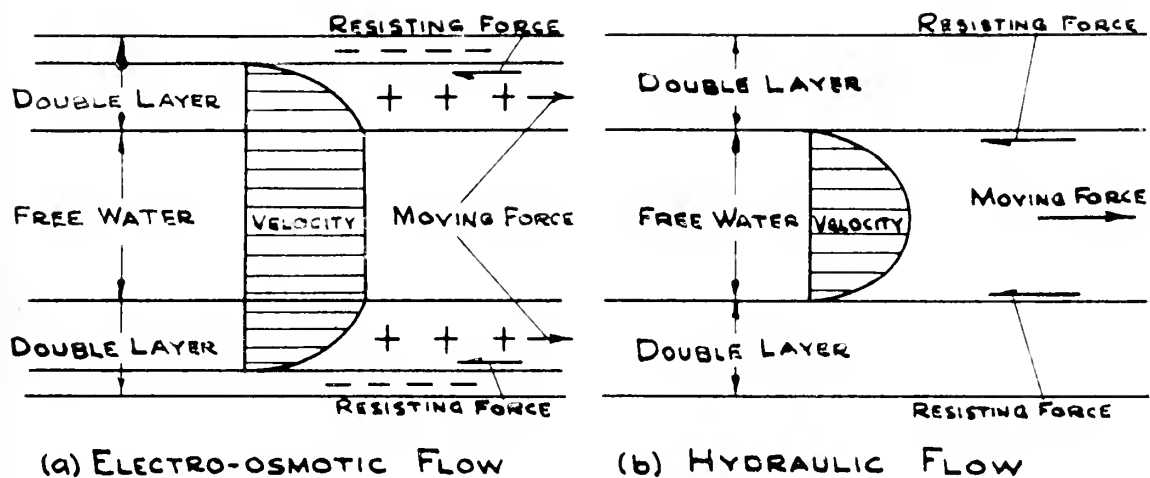
tend to decrease the effective thickness of both the rigid and diffuse layers. The concentration may become such that it will cause such a decrease in the thickness of the double layer that it will eventually collapse. If the double layer is collapsed the Zeta potential will be zero and may reform with the sign of the diffuse layer reversed. In this case, the sign of the Zeta potential will be reversed also and flow will occur in an opposite direction.

Schaad (13) indicates that Helmholtz neglected to delineate several remarkable influences of electro-osmosis in his formula . Not only does electro-osmosis occur but electrolysis also takes place as a result of the galvanic current in the capillaries. It causes the decomposition of the liquid. Furthermore, the conductivity of the soil particles is neglected. The Helmholtz formulae indicate that from a capillary of infinite diameter an infinitely large electro-osmotic discharge would result and this is contrary to every test result.

Perrin who modified the Helmholtz theory presents the double layer theory very well and because of its clarity it is presented here. Perrin considered a capillary tube filled with water subjected to an electrical potential as shown in Figure II.

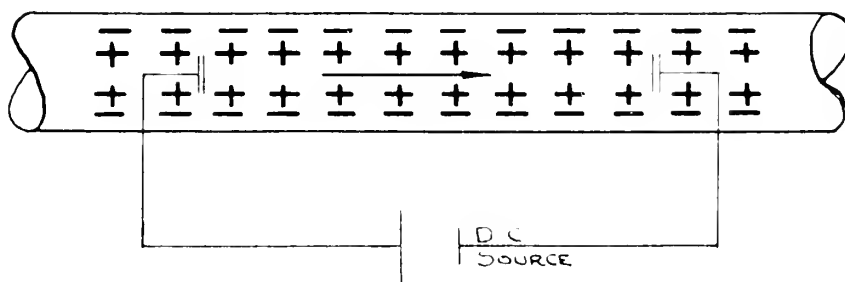
Perrin (15) indicated that if the electrodes are connected to an external direct current source, causing a current to flow in the liquid, the inside of the capillary





COMPARISON OF ELECTRO-OSMOTIC FLOW WITH HYDRAULIC FLOW IN A SINGLE CAPILLARY

FIGURE 1



ELECTRO-OSMOTIC FLOW IN A CAPILLARY TUBE

FIGURE II

behaves as if it had an electrical double layer coating. The outer layer next to the wall of the tube has an excess of anions and the inner layer in contrast to the free liquid in the tube has an excess of cations. In the presence of electro-osmotic force the anions in the outer layer tend to migrate toward the positive pole and the cations in the inner layer toward the negative pole. The outer layer adheres to the wall of the capillary tube thus preventing movement of the liquid in this layer. The inner layer is free to move and the migration of the cations toward the negative electrode sets up a motion of the liquid in this layer which is transmitted by friction to the rest of the liquid in the tube.

To briefly summarize the foregoing: In a soil-water mixture there are numerous capillary tubes integrated to form a capillary system. In each capillary tube the water films consist of a rigid water molecule layer adjacent to the capillary wall and a diffuse layer of a much larger size outside the rigid layer. If this system is subjected to an electrical potential and if the diffuse layer is composed of cations the liquid will tend to move toward the negative pole. The water in the capillary will be dragged along with the moving diffused layer and water will be discharged from the capillary. This electro-osmotic flow due to the phenomenon of electro-osmosis.



Passing electrical current through a soil-liquid system has many more effects than that of electro-osmotic flow. These effects will be discussed in subsequent paragraphs of this section of the thesis.

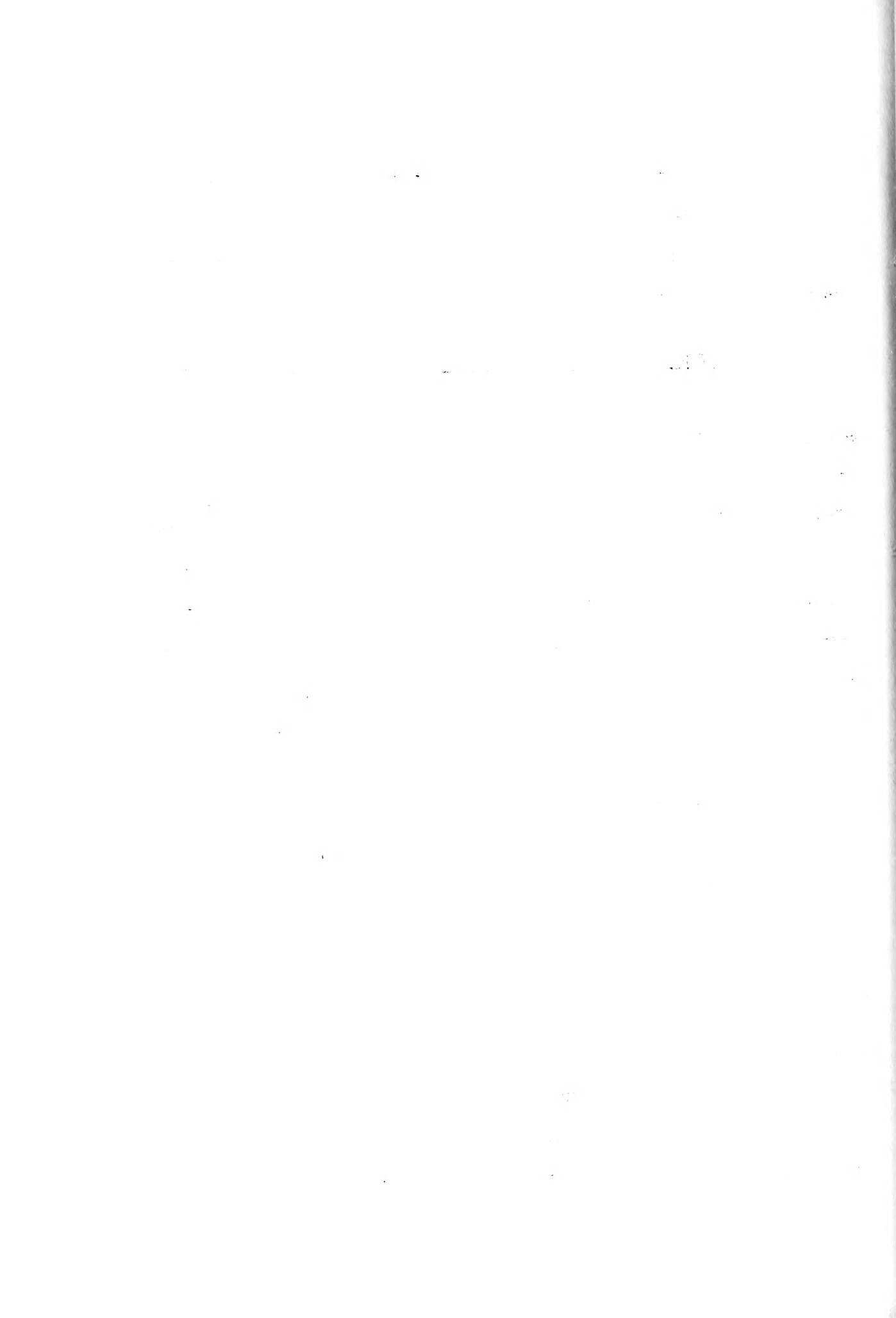
C. Effects of Electro-osmosis on a Soil-Water system

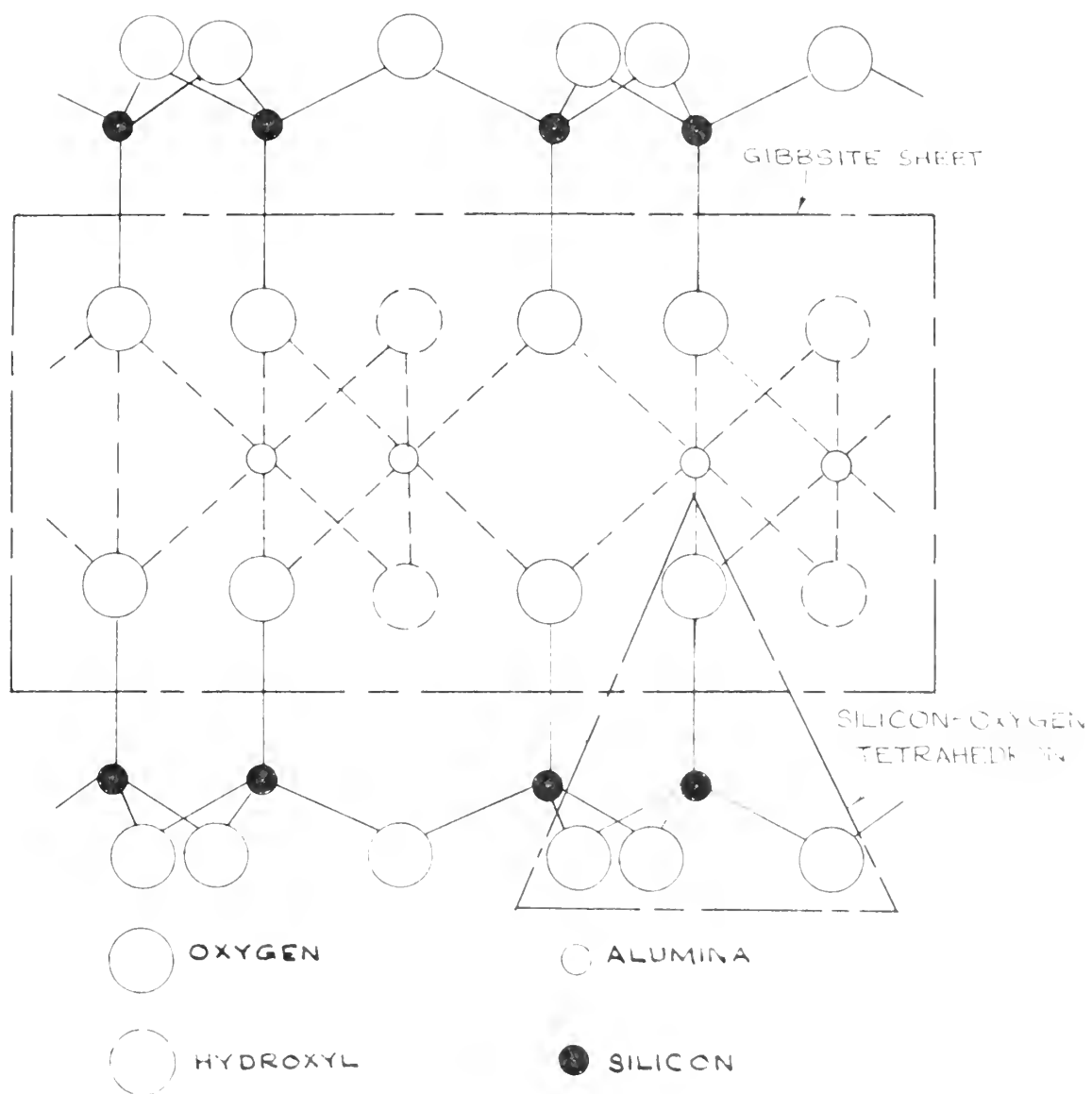
If we are to gain a better understanding of the enigmatic effects of electro-osmosis on a soil-water system, it is necessary that the fundamental knowledge concerning clays and their activities in solution be clearly delineated.

In general, clays may be considered as dispersed systems of the colloidal products of weathering in which secondary mineral particles of smaller dimensions than two microns predominate (1). Clays are crystalline substances which are divided into three major sub-groups namely, kaolinite, montmorillonite and illite. Since illite clay was used exclusively in this investigation, it will be the only clay discussed in detail even though many of the laws which apply to illite could apply equally as well to other clays.

The composition of the illite lattice is similar to that of montmorillonite, because it consists of one gibbsite sheet located between two tetrahedral silicon sheets as pictured in Figure III.

Baver (1) states, "the gibbsite or alumina unit consists of a sheet of closely packed oxygen atoms or





ILLITE SPACE LATTICE
FIGURE III

hydroxyl groups which are held together by aluminum atoms in such a way that one aluminum is surrounded by six oxygen atoms or hydroxyl groups, three from each sheet. The silica unit consists of a sheet of oxygen atoms that are held together by silicon atoms. The silicon atoms are surrounded by four oxygen atoms, three in the sheet and one above. The oxygen atom above the sheet provides the means for linking a silica unit to the gibbsite sheet, since it can serve as one of the six oxygen atoms which surround the aluminum in the gibbsite sheet".

As is true with most clays, illite may be subjected to the process of base exchange when the original liquid of the soil-water mixture is replaced by one containing different ions. If this action results in a decrease in the degree of hydration or in a lower net charge, the new ions may replace the ions of the original double layer either in whole or in part. This is base exchange. Base exchange can be explained simply by the fact that the electrostatic forces within the structure want to be balanced. Base exchange can occur within the lattice-structure of a clay or external to the lattice.

Accordingly, the silicon atoms in each of the tetrahedral silicon sheets may be replaced by aluminum atoms of lower valence which results in unsatisfied valences. In the illites this unbalanced charge is primarily balanced by potassium ions. This results in a

strong bond between adjacent sheets. In view of the above, the base exchange in illites would take place primarily on the cleavage areas of the primary interface as well as the edges and corners. It is realized that the above dissertation on base exchange is brief but it is believed that it is sufficiently detailed to allow the reader to more clearly understand the reactivities associated with electro-osmosis that extend beyond the mere detail of transporting of a liquid through a capillary system.

Probably the most significant reactivity associated with electro-osmosis is that of electro-chemical hardening which appears to be directly related to base exchange. Endell and Hoffman (6) state that "this hardening is apparently brought about by a change in electrical charge on the clay particles, caused by the passage of the electric current through the clay". Previous studies indicate conclusively that electro-osmosis has a stabilizing effect which is distinct from the increased stability due to the consolidation effect alone.

Winterkorn (19) postulates in the consideration of physico-chemical activity of the internal surface it would seem that if the proper anode was chosen it would be possible to introduce desired cations into the soil-water system which could be fixed by the internal soil surface. Winterkorn and Moorman (20) ran a series of tests on homo-ionic clays to determine the influence of different ions

on the consolidation rates and load-void ratio relationship. He determined that the coefficient of consolidation was the smallest for the sodium ion saturation and largest for the potassium ion saturation. From his load-void ratio curves it could be easily seen that certain ions were causing the void ratio to be greater for one hundred percent consolidation under varying load increments, than for the natural sample.

Leo Casagrande discovered that if the anode was composed of aluminum electro-osmosis produced irreversible hardening in clays. The samples were placed in water and allowed to soak for long periods of time (about two and one half years) without losing their acquired strength. Metals other than aluminum, however, produced only temporary strengthening which was lost after slaking in water for a short time.

Endell and Hoffman (7) state that, "the extraordinarily small compressibility of the treated soil suggests that the hardening process goes hand in hand with the development of some sort of structures,". Most investigators agree that the apparent influence of electric current on a disturbed soil is that it tends to regain the properties it had in its undisturbed state after a short period of electrical treatment.

Although sufficient data is not available to determine the exact nature of electro-chemical hardening,

it is certain that it is closely allied with base exchange activities in the clay-water mixture. It would appear that electro-osmosis produces three consolidation effects on the soil sample which are: firstly, the rate of water drainage and the amount of water drained from pore spaces of the sample are substantially increased. Secondly, consolidation caused by electro-chemical hardening seems to be a substantial factor, and finally, the tension produced in the pore water results in a corresponding amount of consolidation in the soil grain skeleton.

Leo Casagrande (3) definitely supports the idea that some of the consolidation is produced by pore water tension. However, Bernatzik (2) dogmatically states that the consolidation and cracking which appear in a soil under the influence of an electrical potential is not caused by electro-osmosis but by an electro-chemical process which is dependent upon the electrode material and the ionization of the pore water.

Endell and Hoffman (7) sum up the present day knowledge of electro-chemical hardening by stating that it is an extremely complicated process whereby the change introduced by the electro-osmotic process gives rise to an exchange of the exchangeable cations bound on the clay particles.

Electro-osmosis effects the soil in many other ways. It changes the liquid limit, plastic limit and plasticity index of the soil. Most investigators agree that the value

of these factors is somewhat higher in the untreated sample than those subjected to electrical potential. However, Endell and Hoffman (7) and Christensen (5) found that the liquid limit values are increased by treatment.

Schaad (13) indicates that, "the disturbances caused by electrolytic decomposition of the liquid and electrodes is considerable. During the tests, polarization of the electrodes, increase and decrease of electrical resistance, and exchange of ions between liquid and soil and even inversion and oscillations of flow were observed. Acidity and basic concentration increases during long permeability tests and change the electrokinetic potential of the double layer and thereby the coefficient of electro-osmotic permeability".

Some authors feel that electrical pre-treatment effects the consolidation process by completing or eliminating the primary consolidation such that upon application of the load it goes immediately into secondary consolidation.

There are probably many other effects of electro-osmosis but the author has only mentioned those that are known and of greatest importance. It can be seen by the foregoing presentation that electro-osmosis is a highly complex process and its effect is dependent upon a multitude of factors. The whole field lies under a veil of partial enlightenment and each investigator merely gives his interpretation of the unknown using his experimental results as a guide line.

It seems to the author that economical application of electro-osmosis is only as distant as that of the correct explanation of the phenomenon involved.

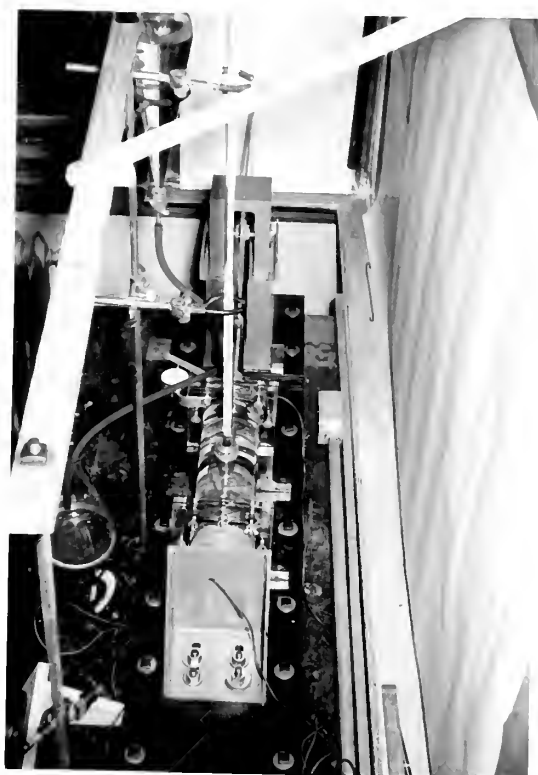
PART III

MATERIALS AND APPARATUS

A. Design

In order to adequately perform the investigation of the effects of electro-osmosis on the consolidation of illite it was necessary to obtain an apparatus that could provide the necessary conditions under which the investigation must be conducted. Since it was necessary that the effect of electro-osmosis on the permeability of illite was to be determined simultaneously with that of consolidation, it was decided that an apparatus similar to that utilized by Schaad and Haefeli (8) would be necessary. This type apparatus was not available among the standard machines possessed by the school nor could any of them be adequately modified to perform the task required. In view of this fact the author and BERNARD E. BUTLER, who was to investigate the effects of electro-osmosis on the permeability of illites, designed the apparatus shown in Figure IV.

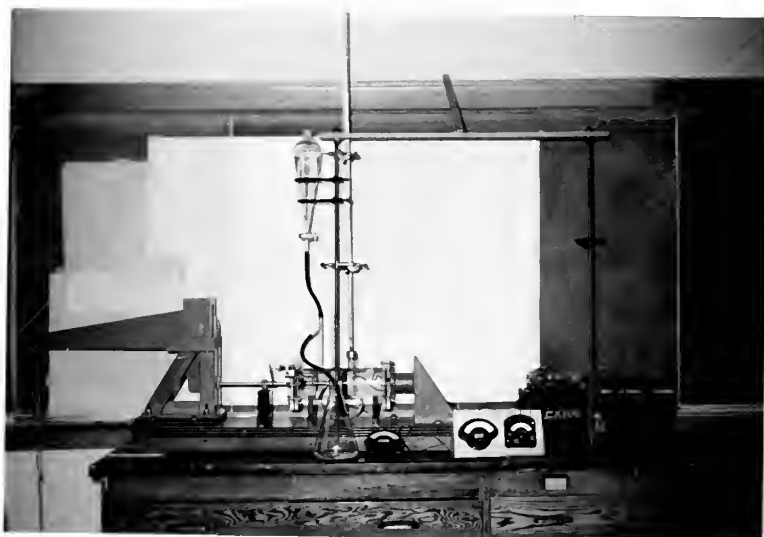
The schematic diagram shown in Figure V clearly indicates the component parts of the apparatus designed and the method in which it was ultimately assembled. The component parts of the apparatus will be discussed in detail in the following paragraphs.



A. Top View of
Electro-Osmometer

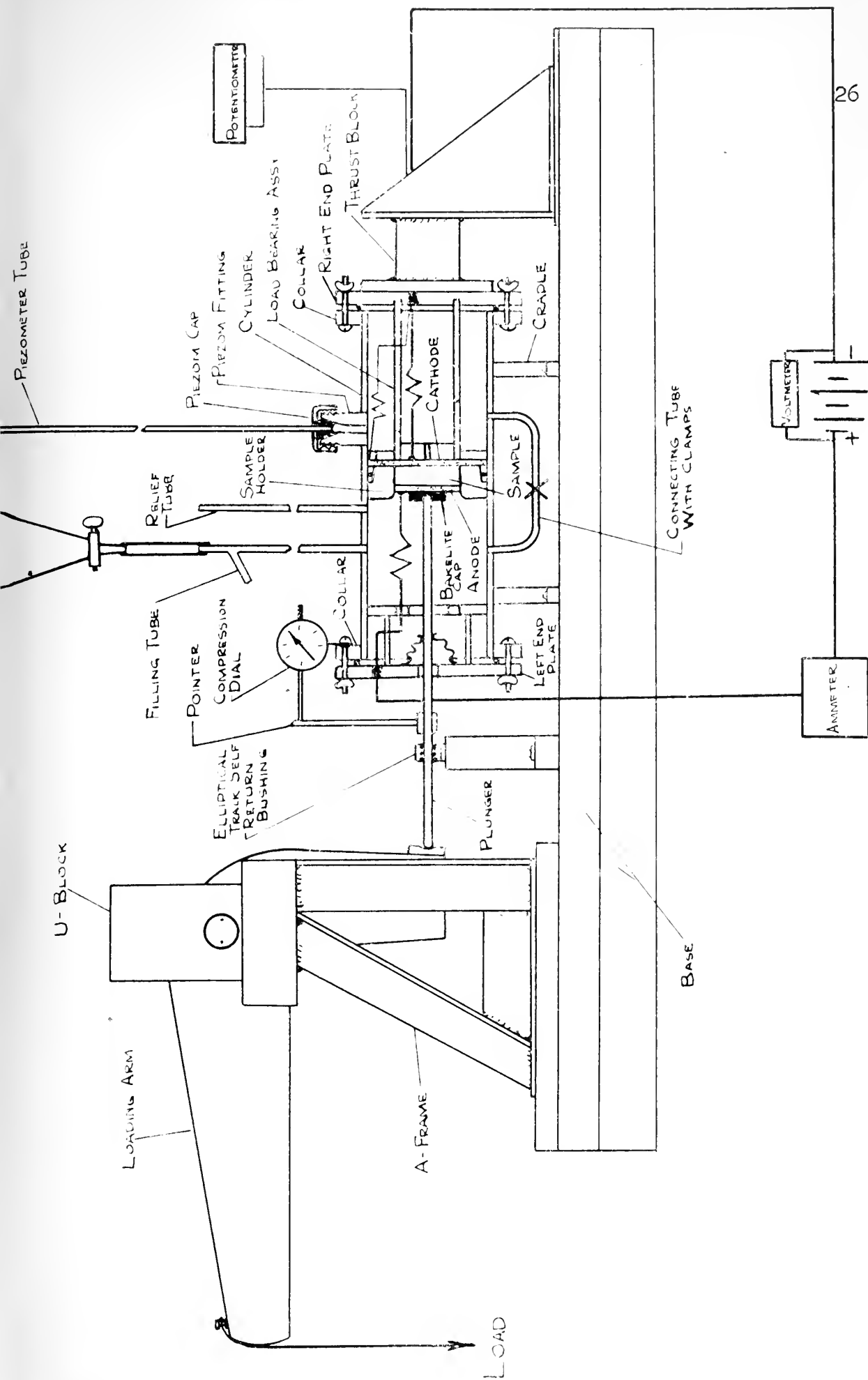
B. Side View of
Electro-Osmometer

A.



B.

FIGURE IV



SCHEMATIC DIAGRAM OF ELECTROSMOMETER
 FIGURE V

The loading arm assembly consists of a loading arm, supporting structure and the pivot housing. The loading arm is composed of an L-shaped plate $1/4$ inch thick. The longer leg is 24 inches long; the other 8 inches long. This ratio of lengths provides a thrust on the sample three times greater than the load applied at the end of the loading arm. The loading arm is suspended on a steel pin which rests on ball bearings located in the pivot housing. Every effort was made during design toward the goal of a minimum development of friction in the moving parts of the apparatus. The pivot block is a U shaped block whose overall dimensions are $7'' \times 4'' \times 5''$. This block was manufactured out of a single block of metal. Its purpose is to support the loading arm. The pivot block is bolted to two "A" structures composed of welded $2'' \times 2\frac{1}{2}'' \times \frac{1}{4}''$ angle irons which make up the supporting structure. The supporting structure is bolted firmly to the base by four $1/2$ inch anchor bolts. The contact plate on the loading arm was drilled to provide a ball and socket arrangement between the plunger and loading arm. This provision later proved to be unsatisfactory and a flat contact plate was installed. In order that some flexibility for alignment purposes could be attained the holes in the platform to which the pivot block is bolted were drilled about $1/8$ inch oversize. This allows a slight movement of the loading arm in any direction and is an excellent feature in making the fine adjustments necessary for good alignment.

For further adjustment the loading arm was mounted on its axle or pin by means of a collar and set screws which allowed considerable lateral movement of the loading arm.

The plunger consists of a $1/2$ inch stainless steel rod, 18 inches long, rounded at the end contacting the loading arm to insure point bearing. At the other end of the plunger a $1\frac{1}{2}$ inch bakelite cap, 1 inch in thickness, was installed to increase the distribution area of the load applied on the porous plate. The face of the cap bearing against the porous plate is well grooved to prevent any undesirable resistance to water entering or leaving the sample. The plunger is positioned by an elliptical track, self-return bushing. The bushing prevents any movement of the plunger except in a horizontal direction which results in a consistent point of thrust application.

The cylinder is constructed of a lucite tube which is 13 inches long and has an outside diameter of $4\frac{1}{2}$ inches and an inside diameter of 4 inches. Two lucite collars, 7" x 7" x $\frac{1}{2}$ ", were fitted over the ends of the cylinder and cemented in place. Two lucite end plates, 7" x 7" x $\frac{1}{2}$ ", were so constructed that they could be easily bolted to the lucite collars attached to the cylinder. A $5/8$ inch hole was drilled in the end plate nearest the loading arm assembly to accommodate the plunger. A rubber seal was then affixed to the inner face of this plate. This seal was unique in that it was required to

allow the plunger considerable freedom of horizontal movement and still prevent leakage of water from the cylinder. The seal ultimately used was an accordian type rubber nipple, one end of which was firmly cemented to the inner face of the end plate and the other end, which had a collar whose inner diameter was something less than 1/2 inch, provided a very tight fit about the plunger.

To provide a water seal between the cylinder and the end plates, 1/2 inch diameter rubber "O" rings were installed between the cylinder collar and the end plate. The seal was established when the cylinder collar was bolted to the end plate. Eight brass bolts were used for this purpose and these were fitted with wing nuts and brass washers. Rubber washers were placed under the brass washers to protect the surface of the lucite. Wing nuts were utilized to allow easy disassembly.

The filling and relief tubes are made of rigid vinyl, 1/4 inch outside diameter and 1/4 inch inside diameter and 8 inches long, firmly cemented to the cylinder. The filling tube is provided with an over flow to allow maintenance of a constant elevation of water. The relief tube is necessary to allow the escape of gases from this particular portion of the cylinder.

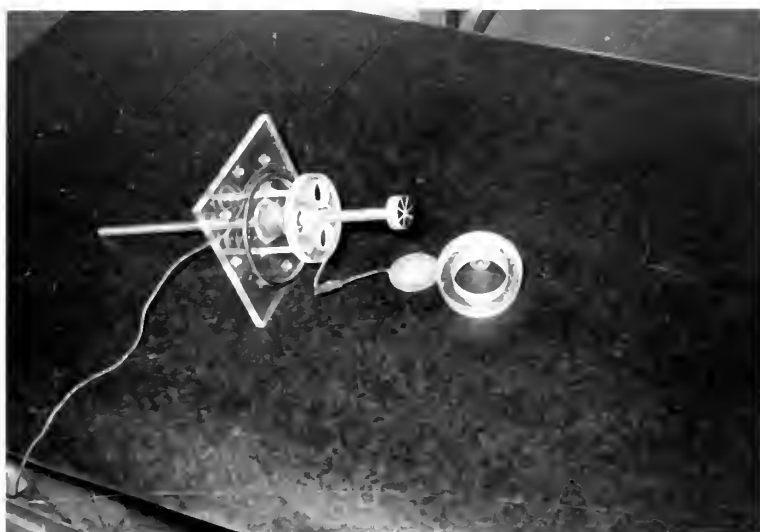
The connecting tube is composed of 1/4 inch inside diameter flexible vinyl plastic. Its purpose is to allow the equalization of water elevation on either side of the

soil sample when the occasion demands. The connecting tube is provided with a stopcock to prevent the travel of water through this route when permeability measurements are being taken.

The piezometer fitting was designed to receive several sizes of piezometer tubes. The piezometer fitting was tapered inside to provide a good seal between the inside wall of the piezometer fitting and the rubber cork cemented to the piezometer tube. The rubber cork is forced into position by a brass cap which is screwed to the top of the piezometer fitting. The rubber cork is provided with a concave surface to a depth of about 1/2 inch to prevent entrapment of gases around the intersection of the cork bottom and the piezometer fitting.

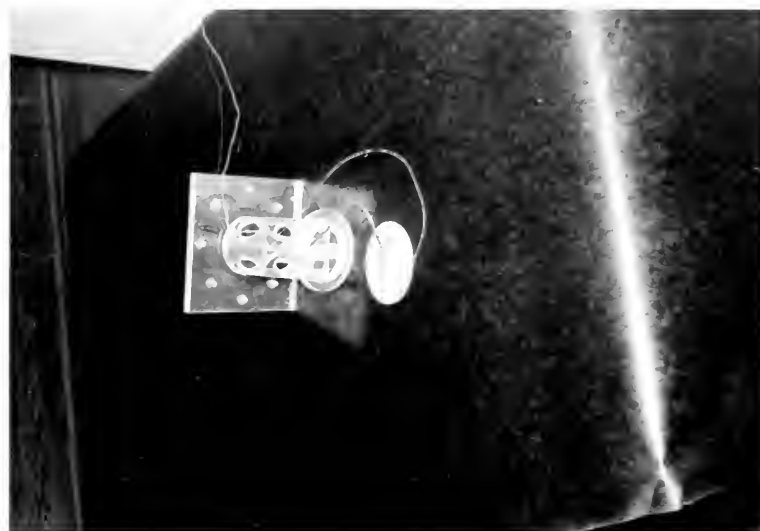
The plunger supporting ring was constructed as an integral portion of the end plate nearest the loading arm assembly which is shown in Figure VI. It consists of a lucite cylinder 4 inches in diameter and 1/2 inch thick which is attached to the end plate by three lucite columns 1/4 inch in diameter. The cylinder is provided with three large holes to allow gas to escape from the area near the end plate. The purpose of the ring is to support the plunger during the process of assembly and to assist the bushing discussed previously in positioning the plunger when load is applied to the sample.

The sample ring, shown in Figure VI, is composed



View of Left End Plate Assembly
and Sample Holder

FIGURE VI



View of Right End Plate Assembly

FIGURE VII

of built up lucite rings having an inside diameter of 2.505 inches. The outside surface was tapered and roughened to provide a watertight seal between the ring and the wall of the cylinder when an "O" ring seal is forced into position between the two surfaces. The inner edges of the ring which accommodates the anode plate were rounded to provide for easy positioning of the anode plate. The ring can accommodate soil samples up to approximately 1-1/8 inches in thickness.

The load bearing assembly, pictured in Figure VII was included to transmit the thrust from the sample to the thrust block. This assembly is a cylinder constructed of lucite which has a reinforced head nearest the sample to allow equal distribution of thrust on the porous plate. The cylindrical portion of the load bearing assembly was provided with eight large elliptical holes to allow the gases forming at the cathode an easy escape route to the piezometer tube. The end plate nearest the thrust block was appropriately grooved to a depth of 1/4 inch to adequately position the load bearing assembly.

Since it was believed undesirable to attempt to anchor the cylinder to the wood cradles supporting it in order to resist the thrust provided by the loading arm assembly, a thrust block was employed. The thrust in this arrangement is transmitted from the plunger to the sample thence to the load bearing assembly and finally to the

thrust block which is securely bolted to the base of the apparatus. The base of the thrust block was slotted and the slots were made wider than the diameter of the anchor bolts in order that proper alignment could be accomplished and that the face of the thrust block would make perfect contact with the face of the end plate. Holes were drilled in the thrust block to accommodate the electric circuit wire running from the cathode to the ammeter.

A removable brass pointer mounted on the plunger between the bushing and the end plate and a deflection gauge mounted on the collar of the cylinder provided a means of determining the amount of consolidation the sample was undergoing under various loading conditions.

The base is composed of 1-1/2 inch plywood, stepped in appropriate locations to allow the thrust application to be maintained on a straight line from the loading arm to the thrust block. The base was heavily reinforced with two $2\frac{1}{2}$ " x $2\frac{1}{2}$ " x $1/4$ " angles to prevent the upward deflection of the base resulting from the couple action established when load is applied to the loading arm.

A glass reservoir with stopcock was installed to provide a sufficient water source to the filling tube in order to maintain a constant head of water. The reservoir is particularly valuable when the apparatus must function for long periods of time unattended.

In order to conduct the type of test anticipated

it was learned after some investigation that a constant voltage electrical source was essential particularly as far as permeability determinations was concerned. It was ultimately determined that a direct current power source in the form of a new six volt storage battery could be utilized without excessive fluctuation in voltage. Plans were made to install a trickle battery charger so that the battery would be at a constant level of charge thereby alleviating the possibility of voltage change due to excessive electrical discharge of the battery. However, the first tests conducted indicated that the drain on the battery was very small and that the battery need only be charged after each series of tests were completed.

Rubber-covered six-strand copper wire was utilized throughout the electrical circuit. Wire of this size was chosen to reduce losses due to the resistance normally encountered in a wire that is too small.

A double range voltmeter, Model 280, Number 113941 manufactured by the Weston Electrical Instrument Corporation of Newark, New Jersey, was installed in the circuit to determine the consistency of voltage values during the tests.

A triple range ammeter, Model 269, Number 151184 manufactured by the Weston Electrical Instrument Corporation of Newark, New Jersey, was employed in the circuit to determine the resistance the sample offered to the flow of

current as drainage of water and consolidation was affected. The ranges of the ammeter are 0-15 milliamperes, 0-75 milliamperes and 0-3000 milliamperes. All these ranges were utilized since the ampere readings ranged from over two hundred milliamperes to about six milliamperes.

In order to determine temperature changes in the sample due to the passage of electrical current, a potentiometer Model 1117, Number 2000 manufactured by the Brown Instrument Company was installed and a thermocouple was manufactured for placement in the sample. A more complete discussion of this part of the apparatus will be presented later.

Metallic porous plates composed of nickel and silver were utilized. The anode plate was $2\frac{1}{2}$ inches in diameter and $\frac{1}{8}$ inch thick and the cathode plate was 4 inches in diameter and $\frac{1}{8}$ inch thick. These porous plates are termed as fine grained and have a porosity over ten times that of the illite used for the tests. The head drop in water traveling through these plates is insignificant.

In order that the results gained from tests conducted by using the above described apparatus might be compared to standard material consolidation results, it was decided to use the standard consolidometer manufactured by the Soil Test Company. This apparatus is pictured in Figure VIII. It provides for two drainage surfaces and accommodates the same size sample as the electro-osmometer described above.



View of
Standard Consolidometer

FIGURE VIII

B. Assembly

The schematic diagram shown in Figure V indicates the manner in which the component parts are assembled to construct the electrometer. Although Figure V is self explanatory as far as assembly is concerned there are certain aspects that should be covered here that were not covered in the discussion of design nor will they be covered in procedure.

The attachment of the circuit wires to the anode and cathode was seriously studied and it was ultimately decided to merely silver solder the electrical wires to the porous plates. In order that the solder mounds would not interfere with the proper bearing of the components bearing on the porous plates and the porosity of the plates, the size of the solder mound and its position was restricted. The rubber insulation was peeled from the wires for a length of about $1/2$ inch. By trial and error method it was determined that a strong connection could be made if a $1/4$ inch pool of solder was melted on an area of porous plate previously cleaned with alcohol and then the wire placed this pool before hardening began.

The thermocouple was prepared by stripping the insulation for about $1/2$ inch of both the copper and constantan leads. The wires were then twisted together for mechanical strength and were silver soldered. Since it was found that 30 gauge wires were too fragile for either

spot welding or torch soldering, silver soldering was about the only method available.

According to Storch (16) using the solder for preparing the thermocouple would not affect the results obtained. He pointed out that since both leads are embedded in solder a "double thermocouple" effect results. First a solder copper thermocouple exists, then a copper to solder, solder to constantan and constantan to solder. The solder components of this "thermocouple chain" cancel each other out and the desired copper-constantan relation is left. Because of this thermo-electrical condition the temperature indicated by the copper-constantan thermocouple will be at the point where the thermocouple leads last touch the solder.

Electrical leads to the battery were secured by ordinary battery clips. This type of connection was utilized to allow the unit to be disassembled quickly and easily.

C. Calibration

After the apparatus was assembled it was necessary that it be calibrated to determine accurately the amount of load that was transmitted to the soil sample when load was applied on the loading arm after friction losses were considered. The use of strain gages was considered, then eliminated, because of the complexity of the procedure. Consideration was then given to loading a simply supported

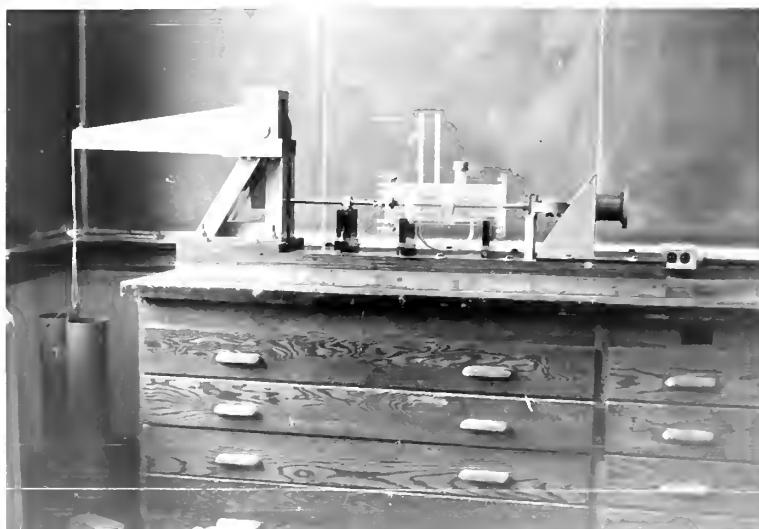
metal beam and obtaining the deflections occurring at each load increment. Then the beam was to be subjected to the thrust from the plunger as various load increments were applied to the loading arm. A comparison of the deflections resulting from calibration of the beam and those occurring during the calibration of the apparatus would provide values of thrust on the sample for various loads applied to the loading arm. However, this procedure was eliminated also because it was felt that the inherent inaccuracies might be excessive. It was finally determined that the simplest method was to use an eleven hundred pound loading ring mounted as indicated in Figure IX. The first results of this method were very discouraging in that they varied considerably from those values obtained by mathematical computation. It was subsequently determined that the load ring that was utilized was improperly calibrated. The load ring was recalibrated by applying known loads and observing the corresponding deflection. The applied weights ranged from zero load to approximately one thousand pounds and a calibration graph was constructed.

The thrust of the loading arm assembly was carried through a 1/2 inch steel shaft to a brass cylinder which was used to simulate the soil sample in the sample ring. This thrust was then transmitted to the load ring by another steel shaft mounted as shown in Figure X. The load ring placed without restraint on wood support was firmly



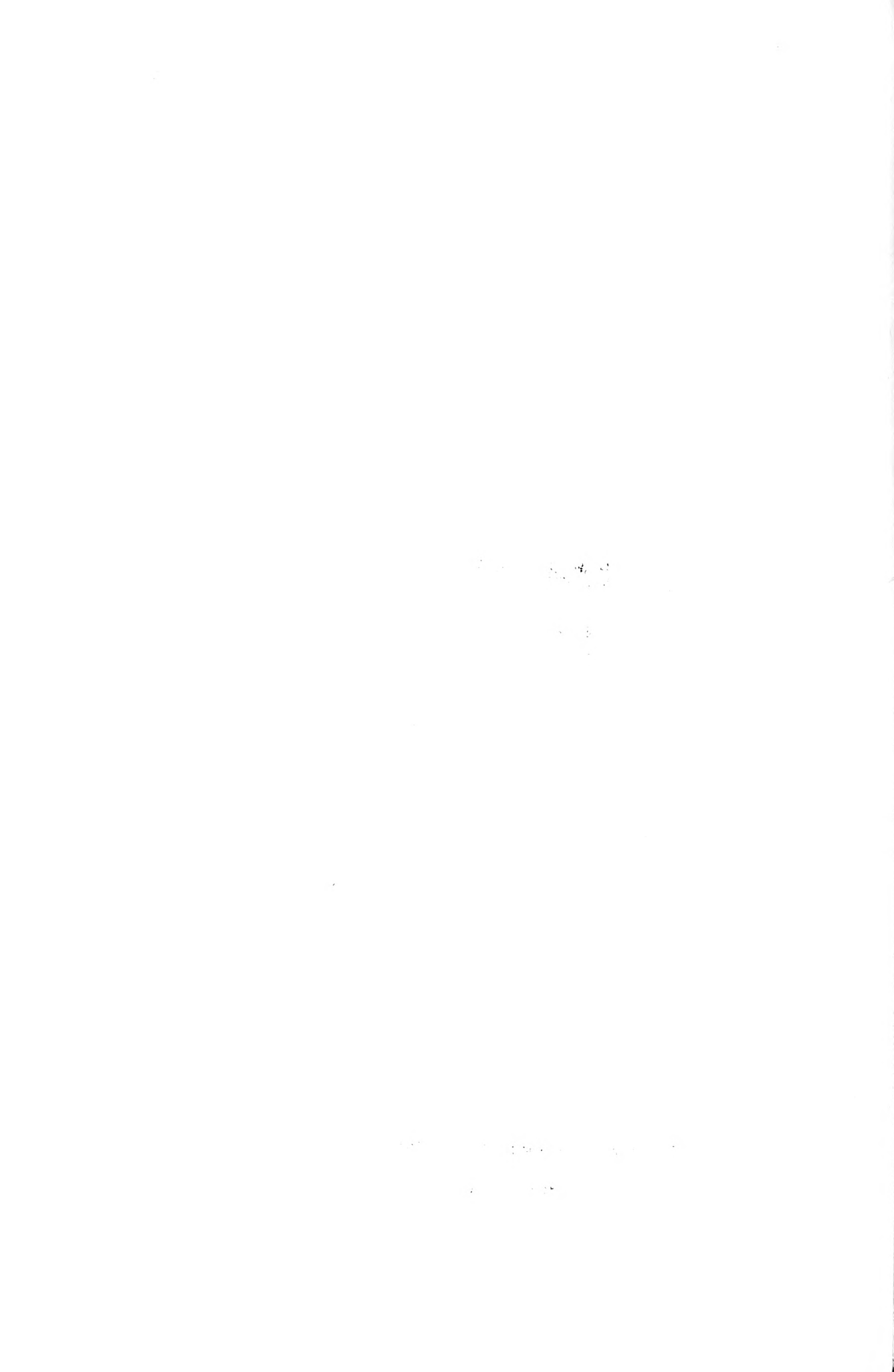
View Showing Detail of
Loading Ring Support

FIGURE IX



View of Calibration Setup

FIGURE X



positioned by the thrust plate of the apparatus. Increasing increments of load were applied to the loading arm and the corresponding deflections were read on a deflection gage appropriately mounted on the ring. It was then an easy matter to convert the gage readings to pounds of thrust. A graph was then plotted of applied load versus load on the sample which is presented in Figure XI.

Upon comparing the results of the above described procedure to those derived by computation it was found that they were in close agreement. It was concluded that friction losses were for all intent and purpose negligible.

D. Soil Sample Description

The name of the soil used in all the tests conducted under this investigation shall be termed "illite". The name illite has been proposed as a general term and not a specific mineral name for the widely distributed clay mineral constituent of argillaceous sediment apparently related to the mica group possessing the general form:

$(OH)_4 Ky(Al_4. Fe_4. Mg_4. Mg_6) (Si_{8-y} - Al_y) O_{20}$. The term illite was proposed by Grim, Bray and Bradley in 1937.

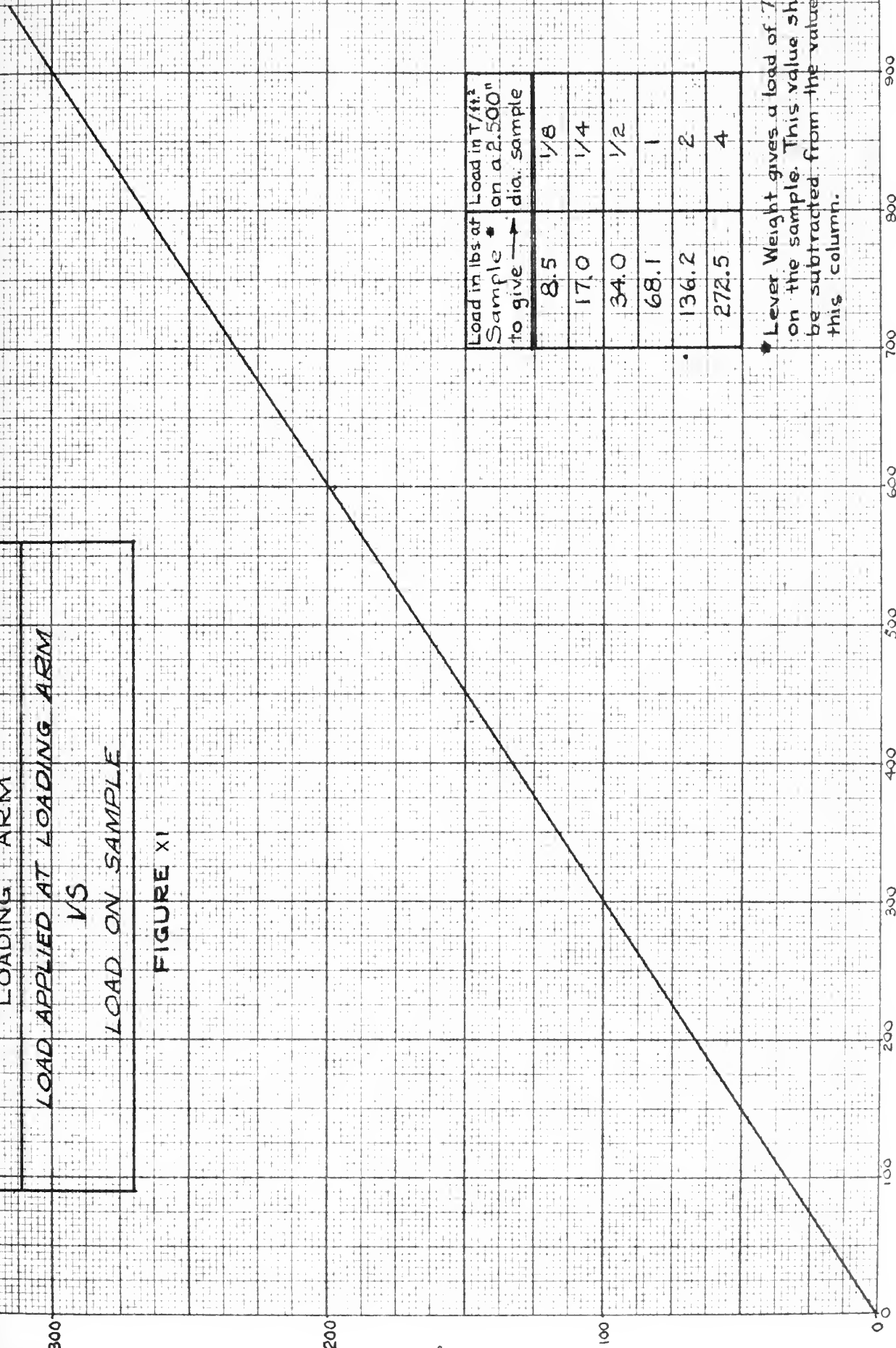
According to the American Petroleum Institute (21), the soil tested occurs in a clay pit of the Illinois Clay Products Company in the Goose Lake area, Northwest 1/2, Northeast 1/4, section 11, township 33H, Range 8E, about seven miles east of Morris, in Grundy County, Illinois.

CALIBRATION CURVE OF ELECTROSMOMETER
LOADING ARM

LOAD APPLIED AT LOADING ARM
VS
LOAD ON SAMPLE

FIGURE XI

Load Applied at Loading Arm in LBS.



Load in lbs. at Sample * to give →	Load in T/ft. ² on a 2.500" dia. sample
8.5	1/8
17.0	1/4
34.0	1/2
68.1	1
136.2	2
272.5	4

* Lever Weight gives a load of 7** on the sample. This value should be subtracted from the values in this column.

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

The soil was taken from the greenish modules in the working face of the "Grundite layer" of clay which lies above the three other clay layers separated by three minor coal seams.

The American Petroleum Institute report indicates that the soil tested was estimated to be 90% pure illite and impurities consisted of 2% quartz, 2% limonite, 2% sericite, 2% plagioclase, about 3% pyrite and a trace of carborate.

To insure that the samples tested contained the percentage illite indicated above and to insure no other clay crystals such as montmorillonite or kaolinite were present, a differential thermal analysis and an X-ray diffraction analysis were performed on the sample. The samples used for these analyses were selected to be as representative as possible and were required to pass a two hundred mesh sieve. C. Heid Jr., conducted the differential thermal analysis on a representative soil sample and concluded that the results of his analysis indicated that the sample was a characteristic illite and that there were no kaolinite or montmorillonite clays present. He also discovered and proved the soil contained a small percentage of organic material. A quantitative as well as the qualitative analysis was conducted by J. Powell using X-ray diffraction method on the soil samples. In general the results indicated that the percentage of illite previously mentioned was substantially correct and that no clay crystals of montmorillonite or kaolinite were present.



A secondary motive was involved in obtaining the X-ray diffraction analysis of soil samples before and after treatment and it lay in the fact that this analysis could adequately serve as a basis for determining whether or not electrical current of the magnitude used would change the crystalline structure of the clay. The results of this comparison will be discussed in the "Results and Discussion" section of this thesis.

In order to further identify the soil tested, a sieve and hydrometer analysis was accomplished. The grain-size distribution curve shown in Figure XII indicates that range of particle sizes is small, i.e., the particle sizes range from 0.420 millimeters to .0006 millimeters but that within this range the distribution is fairly uniform.

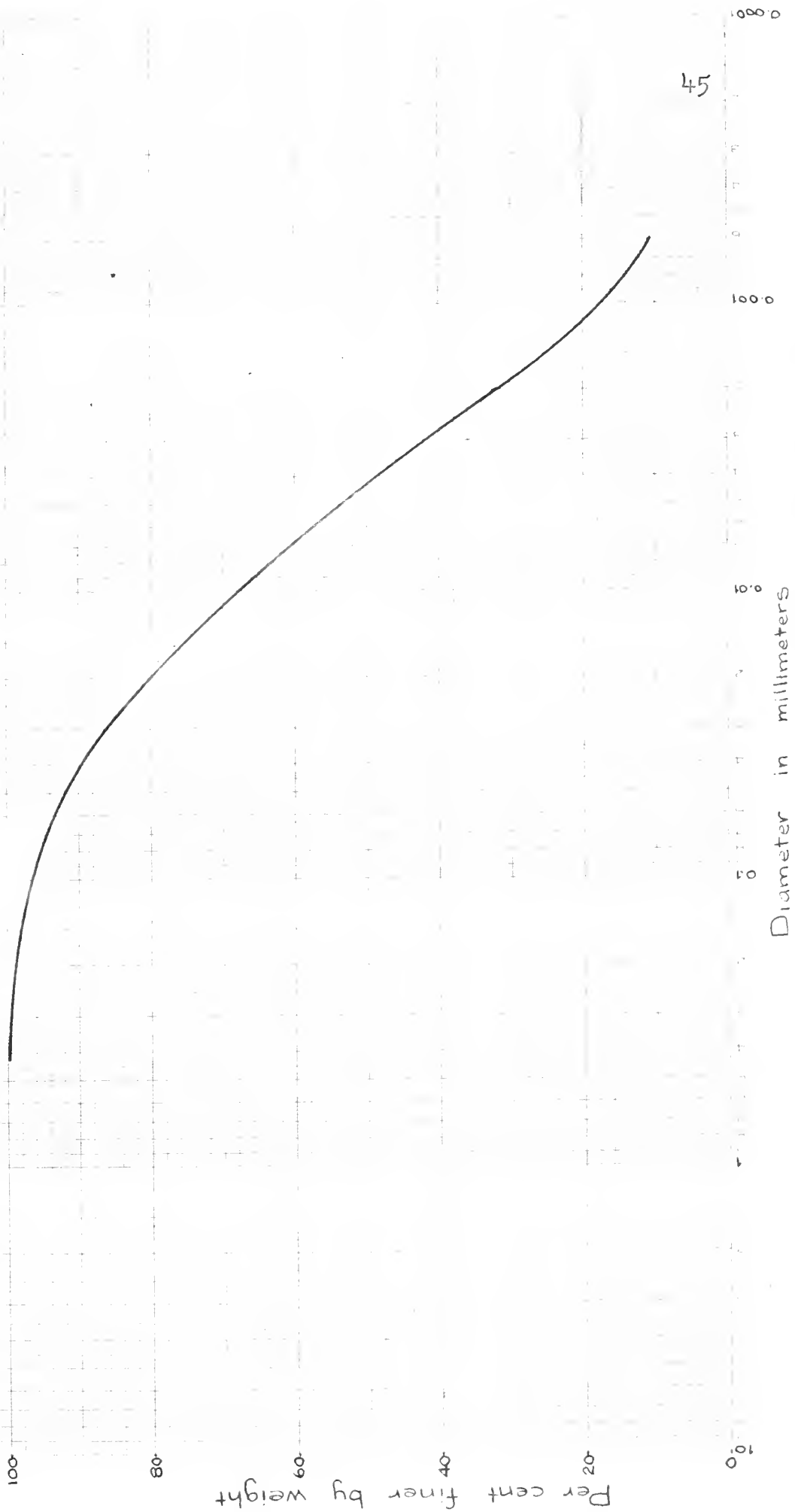
Three tests were conducted to determine the specific gravity of the illite and an average value of 2.76 was obtained.

Since the illite was received in a very desirable powder form grinding was not necessary. As shown by the grain size distribution curve, approximately 95% of the material used could pass a two hundred mesh sieve.

Atterberg limits values were determined for the sample tested. The results of these tests are shown in Table 1. The primary reasons for the determination of the Atterberg limits was to have a basis for comparison for those obtained from the sample that had been subjected to

GRAIN-SIZE DISTRIBUTION CURVE
FOR ILLITE USED IN TESTS

FIGURE XII



electrical treatment.

Since the sample was shipped in a fifty pound bag care was taken at all times to insure that representative samples were utilized in the tests.

The material was thoroughly mixed when it was transferred to the storage bin and when test samples were removed from the bin they were selected by the quartering method on a large sample removed from the bin.

PART IV.
PROCEDURE

A. Sample Preparation

For comparison reasons, it was deemed necessary that the soil samples should be free of all loading effects. This was particularly necessary as far as the consolidation phase of the investigation was concerned. The author felt that the consolidation curves obtained in the tests should all be on the virgin compression portion of the void ratio versus load curve. Therefore, sample numbers 1, 2, 3 and 4 were prepared by the same procedure utilized by Dawson and Mc Donald (6) which is discussed below.

The air-dried soil was thoroughly mixed with a quantity of distilled water necessary to obtain a soil consistency sufficiently stiff to allow the sample to be placed in the sample holder without the soil sample flowing or deforming. Therefore, the water content of the mixture was near the liquid limit. The soil-water mixture was initially tempered by allowing it to remain in an air tight container for about twenty four hours. This step was necessary to allow the soil to gain a uniform moisture content throughout the sample.

Extreme care was taken in selecting the samples to be used in the consolidometer and electro-osmometer. This was necessary so that the two samples used would be

as much alike as humanly possible to make them. The samples selected were then carefully and simultaneously placed in the sample holders for each apparatus with extreme caution being taken to eliminate all possible air voids. The top and bottom surfaces of each sample were then trimmed with a common household type cheese cutter to insure smooth surfaces.

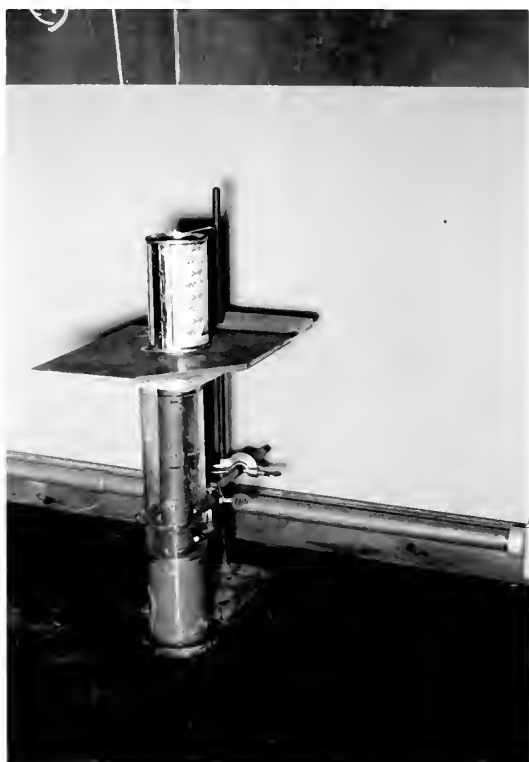
While the first tests were being accomplished, various methods were being studied to create a procedure that would eliminate the obvious inherent unsatisfactory factors associated with the above-described procedure. Unfortunately, a better procedure could not be devised if the pre-loading specification established for the first tests was to be satisfied. The results obtained in the first test for the load increment of $1/8$ ton per square foot were erratic, inconsistent and of questionable value. In view of this fact, it was decided to eliminate this increment. Therefore, it was decided that pre-loading the sample with $1/8$ ton per square foot load increment would not effect the consolidation results desired.

This decision permitted a much more acceptable sample preparation procedure which is outlined below. The air-dried soil was mixed with a known quantity of water sufficient to raise the water content of the soil somewhat above its liquid limit. The soil and water was thoroughly mixed by a household type electric mixer for about five

minutes and the mixture was then transferred to a $2\frac{1}{2}$ inch inside diameter lucite cylinder about 12 inches long. Porous stone plates were placed at the top and bottom of the soil column to allow good drainage. A load was then applied to the sample to cause a $1/8$ ton per square foot load to exist. The pre-loading apparatus utilized is shown in Figure XIII. The soil was allowed to consolidate under this load for a period of about a week which resulted in a soil sample possessing the consistency desired. The advantages of this procedure are, firstly, a more uniform water content in the sample is obtained; secondly, fewer air voids exist in the soil sample and finally, the sample is far easier to place in the sample holders of the machines. Since the diameter of the tube and sample holders are identical. The soil is merely pushed out of the cylinder a required distance into the sample holder and cut off with a steel wire.

B. Assembly of Apparatus.

The assembly of the consolidometer and electro-osmometer should be conducted simultaneously to prevent evaporation of water from the samples. Since two investigators were utilizing the same soil sample in conducting the investigation this requirement could be easily met. The assembly of the consolidometer is a simple straightforward procedure and will not be discussed in any detail.



Pre-Loading Apparatus

FIGURE XIII

However, the procedure involved in assembly of the electro-osmometer is somewhat complex and delicate. It will be discussed in detail in the subsequent paragraphs.

After the soil sample has been properly positioned in the sample ring, i.e., the face of the soil sample is flush with the cathode face of the sample holder, a piece of moistened filter paper is placed over this face of the sample holder to protect the sample. The sample holder is then placed in the cylinder of the electro-osmometer and positioned about $3/4$ inch short of its final location with a large rubber cylinder about 4 inches in diameter. Positioning with the rubber cylinder is necessary since the tolerance between the sample holder and the cylinder wall is very small and binding is very likely unless the positioning force is applied uniformly. Efforts to relieve the binding can easily disturb the sample. When the holder is in its initial position in the cylinder, a rubber "O" ring seal is fitted in the tapered portion of the sample holder. Then the sample holder is driven toward the cathode side of the cylinder to an intermediate position about $1/4$ inch beyond its final position in order to insure that the "O" ring seal is properly seated. Final positioning of the sample holder is accomplished by the load bearing assembly when the right end plate is secured. The filter paper is removed and the cathode plate and thermocouple are put in place followed by the load-bearing assembly, rubber "O"

ring seal and the end plate. The end plate "O" ring seal must be deformed on the top so as to just contact the upper side of the cylinder. This is necessary to prevent the formation of air pockets between the cylinder collar and end plate. The end plate "O" ring seals proved to be unsatisfactory in that it was most difficult to obtain an adequate water tight seal. The seal should be 1/4 inch rubber sheet which makes uniform contact with the entire surface of the collar plate. The right end plate is then bolted into position and the investigator should be careful that the load bearing assembly is properly seated in the seat prepared for it in the end plate. The cylinder is then up-ended to facilitate placement of the anode plate, plunger and left end plate assembly. Care must be exercised in placing the anode plate because it is extremely easy to disturb the surface of the soil sample in this operation.

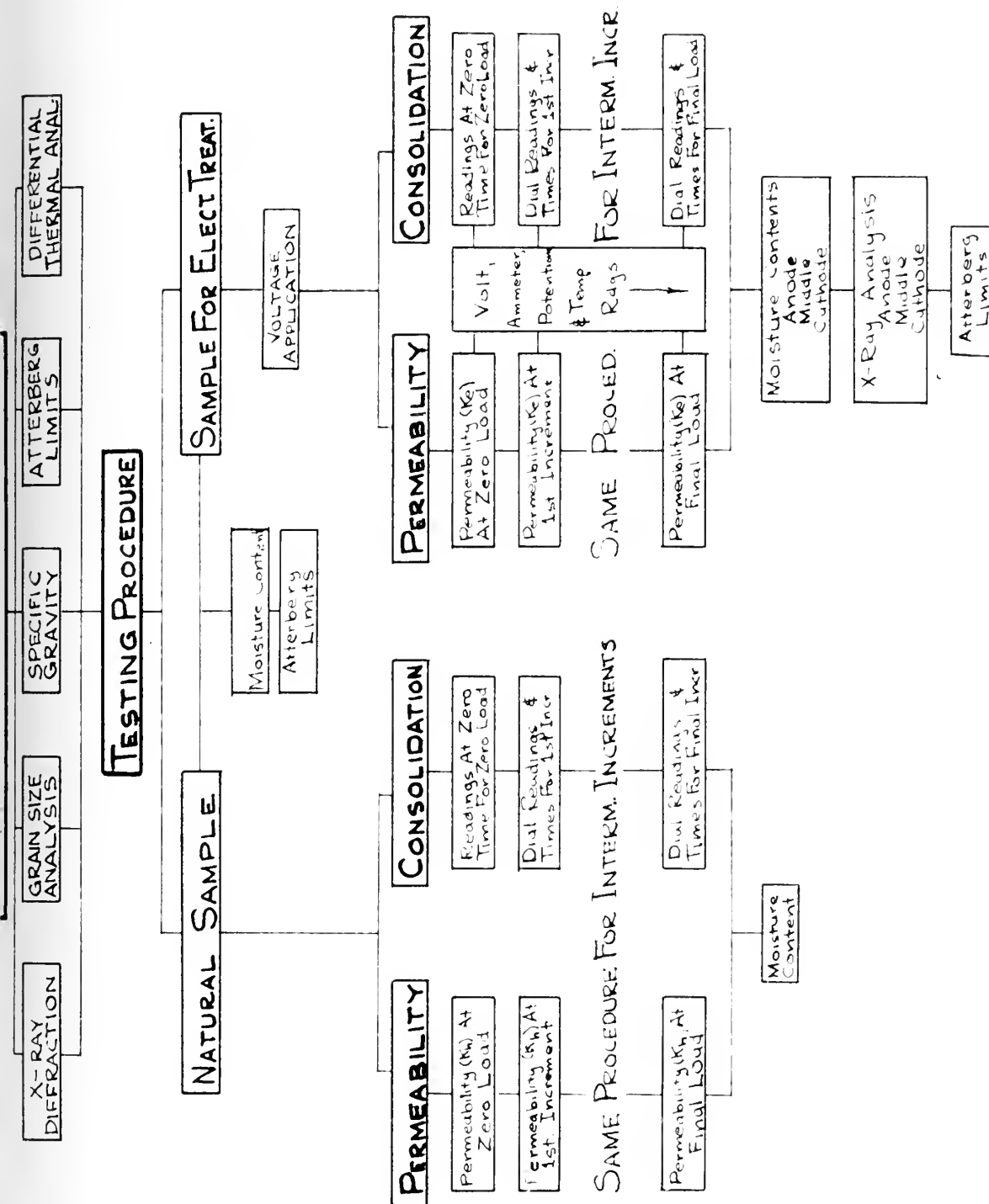
The same steps in positioning the "O" ring seal as indicated above must be applied to placing the left end plate. The deflection gauge and its mounting are attached when the left end plate is installed. The brass pointer is then attached to the plunger and the horizontal thrust bearing is placed on the plunger. The thrust block is then positioned and bolted down. The connecting tube is installed and the cylinder is filled with distilled water. When the cylinder is full and all the air pockets have been

eliminated the piezometer tube is installed. As soon as the battery and electrical instruments are hooked up the apparatus is ready for testing.

C. General Testing Procedure.

Since it was required that two investigators utilize the same apparatus in conducting their research, it was necessary to develop a testing procedure that would give each investigator maximum information from each test. In order to accomplish this requirement the procedure diagrammatically outlined in Figure XIV was developed and utilized for three of the six tests completed. In order that complete permeability results could be obtained it was necessary that the sample be subjected to the passage of electrical current before any load was applied to the sample. Furthermore, it was necessary to pass electrical current through the sample for some time after it had been consolidated under each load increment. The effect of these requirements on the consolidation phase will be discussed in detail later. Equally as unsatisfactory to the permeability phase of the experiment was the relatively short period of time available for the observation of the electrical permeability after the sample was consolidated under a specified load.

In spite of the above objections usable data was obtained and it is felt that the procedure outlined was as good as might have been expected under the circumstances.



GENERAL TESTING PROCEDURE
FIGURE XIV.

In order to determine the effects of the foregoing objections, sample numbers 3 and 4 were conducted primarily for permeability data. Sample number 6 was conducted for consolidation data only.

As indicated in Figure XIV, test numbers 1, 2 and 5 were first subjected to an electrical potential for a period of twenty to thirty hours before load was applied, then the first load increment was applied and the sample was allowed to consolidate. After one hundred percent consolidation was obtained, the electrical permeability test was conducted for a period ranging from two to six hours. This procedure was repeated for successive load increments of $1/4$, $1/2$, 1, 2 and 4 tons per square foot.

Procedure at the beginning of each of tests numbers 1, 2 and 5 was changed slightly to accommodate necessary changes which were manifest in previous tests. In the first test the initial load increment was $1/8$ ton per square foot but was eliminated in subsequent tests for reasons previously mentioned. In the second test the $1/4$ ton per square foot load increment was the first load increment applied. Test number 5 was different in that the sample was pre-loaded to $1/8$ ton per square foot and was then subjected to electric potential. In tests numbers 3 and 4, which were conducted primarily for permeability data, the samples were pre-loaded with a load of $1/4$ ton per square foot and electric current was applied for a

period of about four days. In these tests subsequent load increments were not applied.

Test number 6 was conducted primarily for consolidation data, therefore, no time was utilized in conducting electrical permeability tests before loading or after each load increment had consolidated. In this test the soil sample was pre-loaded with a load of $1/8$ ton per square foot. The purpose of this test was to determine the effect of the permeability tests on the results of consolidation phase of the investigation.

For each load increment's consolidation period and for each period of electrical permeability determination piezometer, deflection gauge, ammeter, voltmeter, room temperature and potentiometer readings were taken at specific time intervals especially during the consolidation period. Readings were taken for the consolidation phase at the following time intervals measured from "0" time, .25, .5, 1, 2, 3, 5, 10, 15, 30, 60, 120, 240 and 1440 minutes.

The sample was then removed from the apparatus and water content was determined at the anode surface center and cathode surface of the sample. Atterberg limits tests were also conducted on the sample. The samples removed for water content were made unusually large so that they could be utilized for X-ray diffraction and differential thermal analysis.

The test specimens for each apparatus were

prepared to a pre-determined height and weighed before they were placed in the sample holder. This procedure was necessary for void ratio determination.

As indicated in Figure XIV a corresponding sample placed in the consolidometer was subjected to the same load increments as that in the electro-osmometer for each test conducted. The purpose of this action was to provide a basis of comparison in order that the effects of electro-osmosis on consolidation might be evaluated. Deflection gauge and time readings were recorded for the same time intervals as those indicated for the electro-osmometer. Hydraulic permeability determinations were obtained after one hundred percent consolidation was reached under each load increment. The final sample was weighed, dried and weighed again to determine the moisture content and to obtain data essential in computing void ratio.

PART V.

RESULTS AND DISCUSSION

A. General

The purpose of this section is two fold, firstly, to delineate the results obtained from the tests conducted and secondly to attempt to explain abnormal or unexpected results and correlate them with those obtained by other investigators. The attempt to correlate the results of this investigation with those obtained by other investigators is very difficult inasmuch as most literature pertaining to the results of other investigators fail to outline completely the conditions under which their tests were conducted. The most flagrant omission of test conditions was that of an adequate description of the type soil being investigated. In view of this fact correlation will be made only in those cases where the general trend of the results gives strong indication that a particular result would be expected.

The results and the discussion of these results were integrated in this thesis to eliminate duplication, and to provide continuity and clarity.

The results discussed under the "General" sub-heading will concern only those observations which were common to all tests conducted or were of such a nature that they could not be appropriately discussed in other

sub divisions of this section.

Due to the lack of better terminology, the sample subjected to an electrical potential will be known as the "treated sample" and the sample placed in the standard consolidometer will be known as the "untreated sample".

Water Content Changes

Water content determinations were conducted as indicated under the "Procedure Section" and the results of these determinations are shown in Table 2. From studying Table 2, it appears that the only valid conclusion that can be reached is that the water content at the anode portion of the soil sample is higher than those of the other portions of the sample. The water content values for tests numbers 1, 2 and 6 seem fairly uniform for the water content determination at the middle of the sample. The water content determinations for the portion of the samples in the vicinity of the cathode plate were very erratic. There exists a very plausible reason for this and it lies in the fact that free water can be trapped in the cracks and fissures existing in the sample near the cathode plate. The quantity of water in these fissures varies due to the effects of evaporation when the sample is exposed and gravitational drainage when the sample is being prepared for water content determination. In view of the above discussion it can be seen that large variation in water content

TABLE 1
ATTERBERG LIMITS

SAMPLE NO.	BEFORE TREATMENT			AFTER TREATMENT		
	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX	LIQUID LIMIT	PLASTIC -LIMIT	PLASTICITY INDEX
1	56.6	29.11	27.5	65.0	30.4	34.6
2	56.6	30.2	26.4	66.0	32.2	33.8
3				61.8	34.4	27.4
4				58.5	38.2	20.3
5				63.8	31.03	32.8
6				62.0	32.2	29.8

TABLE 2
WATER CONTENT

SAMPLE NO.	BEFORE TREATMENT	AFTER TREATMENT		
		ANODE	MIDDLE	CATHODE
1	57.3	36.7	36.7	34.4
2	63.0	39.6	37.3	37.8
3	57.34	48.0	46.35	45.47
4	60.2	52.8	55.1	58.6
5	56.7	38.98		38.88
6	55.78	37.4	37.2	41.2

10

11

12

13

14

15

16

17

18

19

20

21

22

23

24

25

26

27

28

29

•

determination of the soil sample near the cathode plate is entirely possible.

Atterberg Limit Value Changes

The results of the Atterberg limit determinations before and after electrical treatment are shown in Table 1.

Only two Atterberg limit determinations were conducted on the soil before treatment because the material was identical for each test conducted and the results obtained in these tests were fairly comparable.

In each test it was noted that the liquid limit and the plastic limit was higher for the treated sample than for the untreated sample. In all except tests numbers 3 and 4 the plasticity index was higher for the treated sample than for the untreated sample.

As indicated in the "Theory Section" most investigators have found that the values of liquid limit, plastic limit and plasticity index for the treated samples are somewhat lower than those for the untreated samples; others have found that the reverse is true. In view of these conflicting results no positive check can be made. Since the results indicated in Table 1 consistently indicate that the values of the liquid limit, plastic limit and plasticity index are higher for the treated sample than for the untreated sample these results are considered entirely acceptable for the type soil used in this test.

Upon comparing the pasticity indices given in Table 1 with the duration of electrical potential application given in Table 3 it was noted that, with only one exception, the greater the total duration of electrical potential application the higher the plasticity index value became.

During the process of slaking and remolding the treated sample for the Atterberg limit determinations, it was noted that the portion sample nearest the cathode resisted the slaking process until a considerable amount of remolding had been accomplished. However, after about five minutes of working the sample with a spatula the clay became slaked. This would tend to indicate that irreversible hardening is not obtained by the use of nickel or silver porous plates. This verifies Casagrande's (15) conclusion that the use of metals other than aluminum for the anode plate produced only temporary strengthening which was lost after slaking in water for a short time.

Physical Appearance

The portion of the sample nearest the cathode was flaky and fissured in appearance for a depth of about 1/8 inch. The color of this portion was a much lighter grey than that of the rest of the sample. The color was not uniform throughout this 1/8 inch layer, but was interlaced with patches that were almost black and those of a blue-

TABLE 3

DEVIATION FROM LINEARITY FOR EACH PHASE OF TESTS CALCULATED

1012 IN. IN. PHASE	1/g		1		1/2		I		P		H	
	c	k	c	k	c	k	c	k	c	k	c	k
k - porosity 1.18												TOTAL
1	1,730	1,125	311	1,135	6	1,800	225	1,437	22	970	146	1,773
2	1,816	0	0	1,720	0	1,718	83	1,635	103	1,274	146	1,700
3				0	5,651							
4				0	305							
5	0	1,111	1,715	305	1,110	305	1,110	1,145	1,138	75	960	140
6	0		7	7	60	0	7	7	74	0	77	0
												1,600

10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100

green hue. Portions of this part of the sample were very brittle and flaky while other portions were very hard and compact. The rest of the sample appeared much the same as it did before treatment, except, of course, it had greater strength and was somewhat drier. The above observations seem to bear out Casagrande's (3) conclusion that a remolded soil subjected to an electrical potential tends to develop a structure "which is similar in appearance to that of clay in its natural state".

Expansion Effects

After each load increment had fully consolidated the sample, the water in the piezometer tube was lowered until it equalled the height of the water in the over-flow tube. Each time this action was accomplished it was noted that the deflection gauge indicated a small amount of expansion was occurring in the sample. This was due to the fact that a head of water was acting on the sample caused by the rise of water in the piezometer tube. When this head of water was decreased the clay sample expanded or rebounded due to the decreased effective thrust on it.

Electrical Current and Voltage Changes

As shown in Figure XV, the time versus current curves for tests numbers 1, 2, 5 and 6 are characteristic. When the electricity was first applied to the soil sample, the ammeter was recording approximately 220 milliamperes

CURRENT VS TIME CURVES
FOR
SAMPLE NOS. 1, 2, 5 & 6

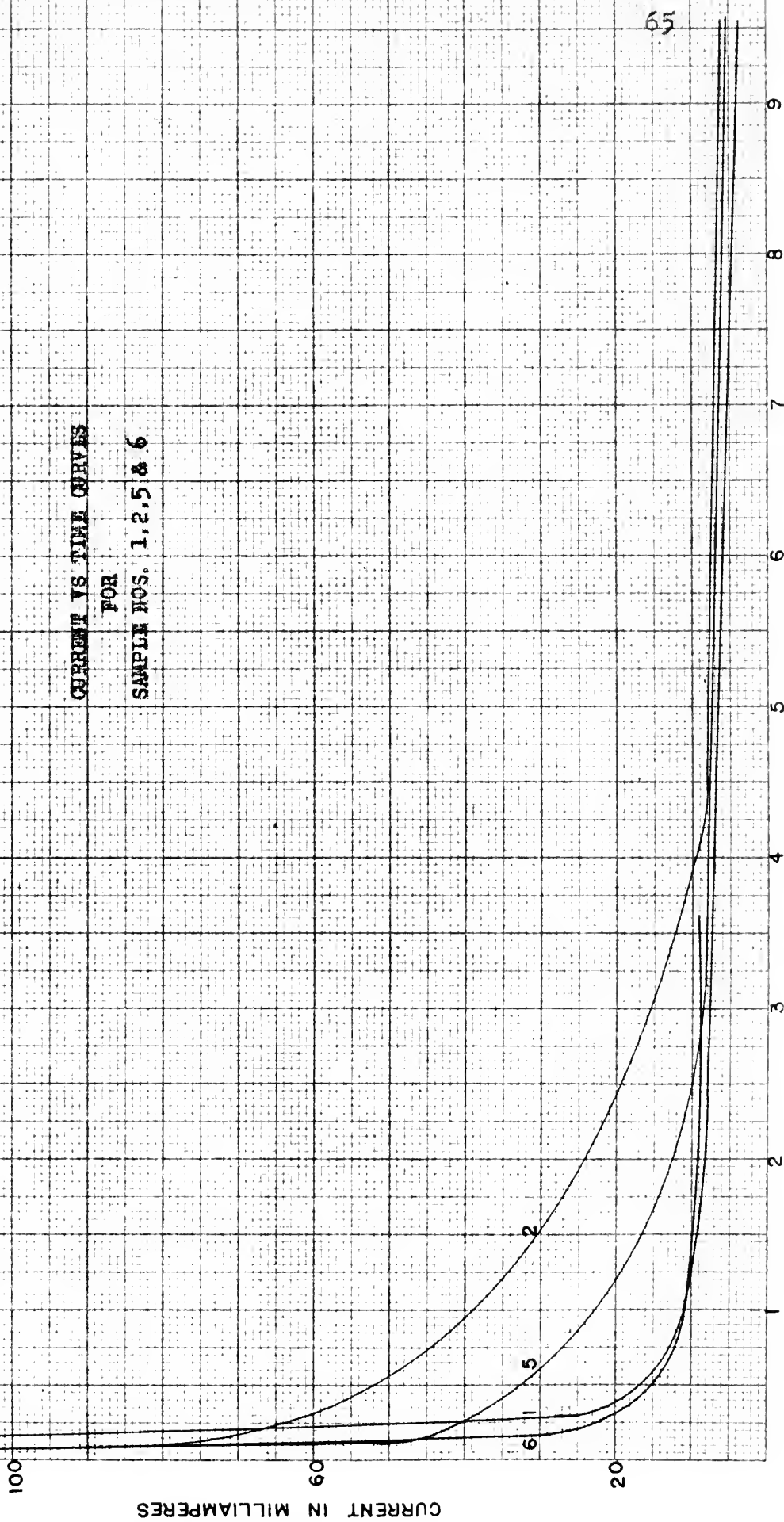


FIGURE XV

for each test. There were deviations, of course, because of differences in sample thickness and water content. The amperage values decreased very rapidly during early part of the tests and then leveled off at a value of 5 to 7 milliamperes. The amperage values continued to slowly decrease during the leveling off period.

When each load increment was applied the amperage values would immediately increase in the amount of 0.1 to 0.3 milliamperes. This increase was usually dissipated during the first hour the sample was consolidating under the new load increment. The reason for this increase was probably due to the fact that the water distribution had been somewhat changed due to the compression caused by the new load increment which resulted in reduced resistance to current flow by providing a continuous and a thicker conductor. These fluctuations were not recorded on the curves in Figure XV in view of their ephemeral nature.

It is the author's opinion that the shape of the current curves shown in Figure XV is very closely related to the length of time the sample was subjected to an electrical potential before load was applied. It was noted that for the longer periods of pre-treatment, the break in the initial straight line drop of the current curve occurred at higher amperage values and that the curve required a longer time to begin its final leveling off process.

The voltage varied from a value slightly over 6

volts at the beginning of the first test to 5.95 volts during test number 6. The battery was charged once during this investigation for a period of about two hours prior to the beginning of test number 5.

Temperature Differentials

Determinations of temperature increases in the sample due to the resistance offered by the soil was measured. During the zero loading period of test number 1, the temperature differential between the soil sample and room temperature rose to a peak of about 5°C . during the first two minutes of the loading period which was dissipated in a period of forty minutes. There was no further temperature differentials observed until the $1/2$ ton per square foot load increment was applied. The temperature differential reached a peak of 1°C . during the first five minutes of the loading period and was dissipated in about two hours. A temperature differential of 3°C . occurred during the electrical permeability determination after the $1/2$ ton per square foot load increment consolidation and was dissipated during the one ton loading period.

At the beginning of the two tons per square foot loading period a 1°C . during the electrical permeability determination for this increment. It then decreased to 1°C . during the four tons per square foot loading period and finally increased to 3°C . during the electrical

permeability determination for this load increment.

During tests numbers 2, 3, 4 and 5, no temperature differential was noted. In view of the results obtained in test number 1, it was felt that something was wrong with the thermocouple. Therefore, prior to test number 6, a new thermocouple was constructed similar to the one described in the "Materials and Apparatus Section" of this thesis.

During test number 6, a temperature differential of 5°C . was noted after the electrical potential had been applied for three minutes and this dissipated itself in six hours. No further temperature differentials were noted during the remainder of this test.

The author finds it difficult to explain why most of the peak temperature differentials occurred a few minutes after the load increments were added. Common sense would dictate that the greatest amount of heat energy would be generated when the resistance to the flow of electric current was the highest. In these tests it would mean that the greatest temperature differential should occur when the sample is consolidated, because a review of the ammeter readings will show that the resistance to electrical current flow increases as the consolidation process nears completion.

Anode Decomposition

During test number 1, it was noted from visual inspection that there was considerable decomposition of the anode plate. In order to determine the loss of anode material during the test, the anode plate was removed, dried at 110°C . for a period of four hours and weighed prior to test number 2. After the test was completed the anode plate was again removed, dried at 110°C . for a period of four hours and weighed again. It was determined that in a period of two hundred and four hours the anode plate loss amounted to 2.0056 grams. After a period of eight hundred and eighty three hours the thickness of the anode plate was reduced from 0.125 inches to .104 inches.

pH Values

In all tests the liquid in the anode side of the electro-osmometer attained a greenish-blue tint and a fluffy white precipitate gathered at the bottom of the cylinder. The liquid in the cathode side of the electro-osmometer was clear and free of the precipitate. pH values were obtained for the liquid in each side of the cylinder after test number 1 and these values were 5.38 for the anode side and 11.35 for the cathode side.

An elementary chemical qualitative analysis was conducted on the liquid from the cathode side of the cylinder indicated that there were no compounds of nickel, silver



or copper present. A trace of a silver compound was found in the anode side of the cylinder. There was strong indication that copper carbonate and nickel carbonate were present in this liquid. A complete chemical analysis of the soil and water would be necessary before any useful conclusions could be formed on this phase of the investigation.

Changes in Sample Content

Since some investigators have indicated that under certain ranges of electrical potential there was a change in crystal structure of the clay, X-ray diffraction analysis was accomplished by J.E. Powell on the soil samples subjected to electrical potential in tests numbers 1 and 2. In the analysis of both samples it was found that there was definitely no change in the crystalline structure of the clay. This fact was confirmed by C.C. Heid Jr., who performed a differential thermal analysis on the same samples. However, it was noted upon comparing the X-ray spectrometer recordings of the natural sample with those of similar recordings for material removed from positions near the anode, middle and cathode of the treated sample that a foreign material had been introduced and was decreasing the intensity of the illite peaks on these graphs. This fact can quickly be verified by comparing the X-ray spectrometer graph for the untreated illite sample shown in Figure XVI to Figures XVII



90

71

80

70

Specimen No.	Illite (T-B No.1)
Radiation	Cu KV-70 Ma-15
Filter	Nickel
Scanning Rate	1° 29/Min
Scale Factor	8
Multiplier	0.6
Time Constant	8

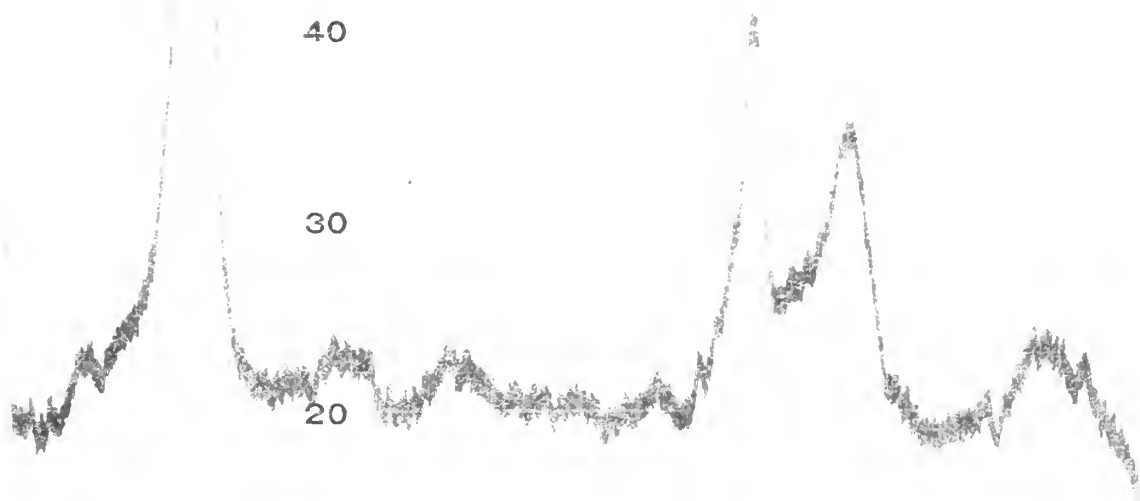
60

50

40

30

20



X-RAY SPECTROMETER TRACE
FOR
10
UNTREATED SAMPLE, TEST NO. 2

FIGURE XVI

0

25°

20°

2θ

90

72

80

70 Specimen No. Illite (T-B No.2)
Anode

Radiation Cu KV-70 $Mn-15$

Filter Nickel

Scanning Rate $1^\circ 2\theta/\text{Min}$

60 Scale Factor 8

Multiplier 0.6

Time Constant 8

50

40

30

20

X-RAY SPECTROMETER TRACE
FOR
TREATED SAMPLE, TEST NO. 2
10

FIGURE XVII

0

25°

20°

2θ

90

73

80

Specimen No. Illite (T-B No.2) Middle
Filter Nickel 70
Radiation Cu KV-70 M_A-15
Scanning Rate $1^\circ 2\theta/\text{Min}$
Scale Factor 8
Multiplier 0.6
Time Constant 8 60

50

40

30

20

10

0

X-RAY SPECTROMETER TRACE
FOR
TREATED SAMPLE, TEST NO. 2

FIGURE XVIII

 25° 20° 2θ

90

74

80

Specimen No. Illite (T-B No.2), Cathode
Radiation $\text{Cu KV-70 Ma-15}^{70}$
Filter Nickel
Scanning Rate $1^\circ 2\theta/\text{Min}$
Scale Factor 8
Multiplier 0.6
Time Constant 8

60

50

40

30

20

X-RAY SPECTROMETER TRACE
FOR
TREATED SAMPLE, TEST NO.2

10

FIGURE XIX

0

30°

25°

20°

2θ

XVIII and XIX which represent the specimens taken from sample number 2. The analysis conducted for sample number 2 is representative for all the test samples analyzed, therefore, only the results of this analysis will be included in this thesis. A comparison of Figures XVII, XVIII and XIX indicate that the peak intensity is the smallest at the cathode and increases to an almost normal magnitude at the anode. From this observation it could be concluded that the greatest amount of foreign material was found at the cathode. Although the sample was not chemically analyzed, it is felt that the foreign material must be some compound of nickel or silver. There was no indication from the X-ray analysis that the methyl orange introduced in sample number 2 had any effect on the crystalline structure of the clay.

B. Test Number 1.

Figures XX, XXI, XXII, XXIII and XXIV represent the results of the test number 1. A comparison of the consolidation curves of the treated sample to the untreated sample on Figures XXII and XXIV reveals a very unexpected result in that it required a longer time to reach the theoretical one hundred percent consolidation in the treated sample than it did in the untreated sample. However, for the other load increments in this test, the reverse is true. It was difficult to get the theoretical initial compression

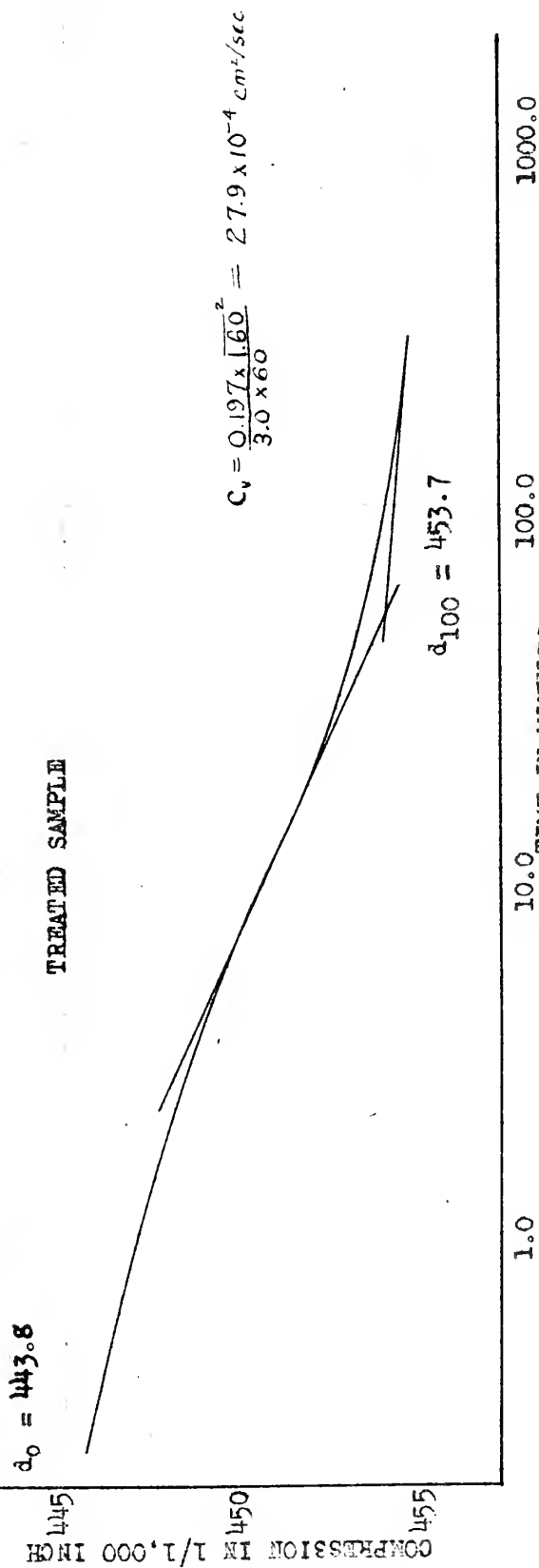
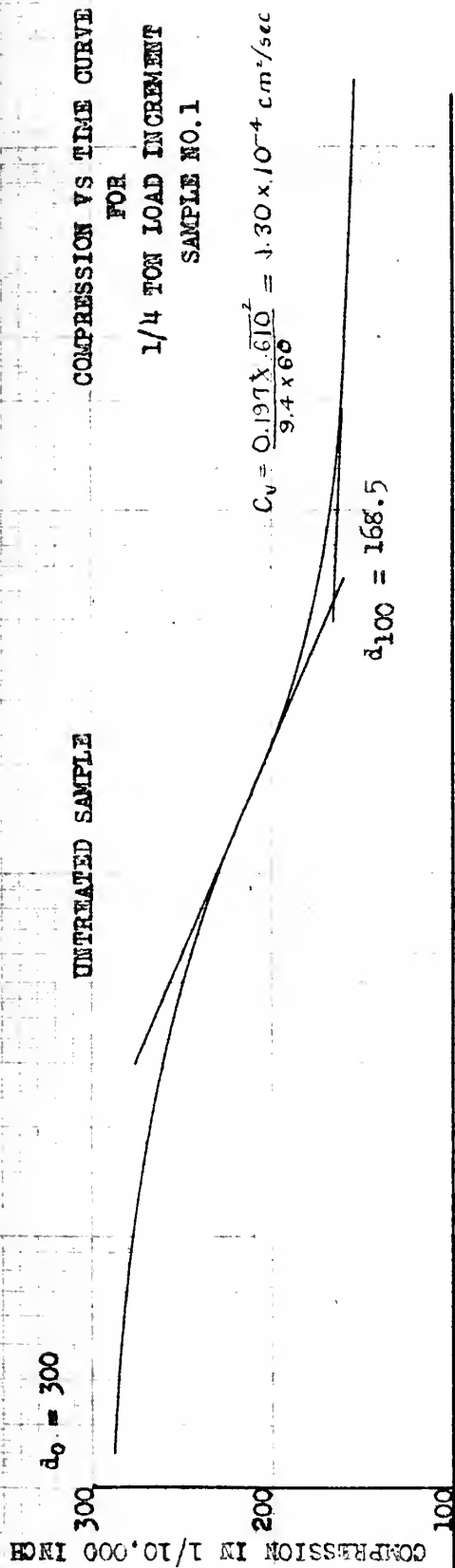


FIGURE XX

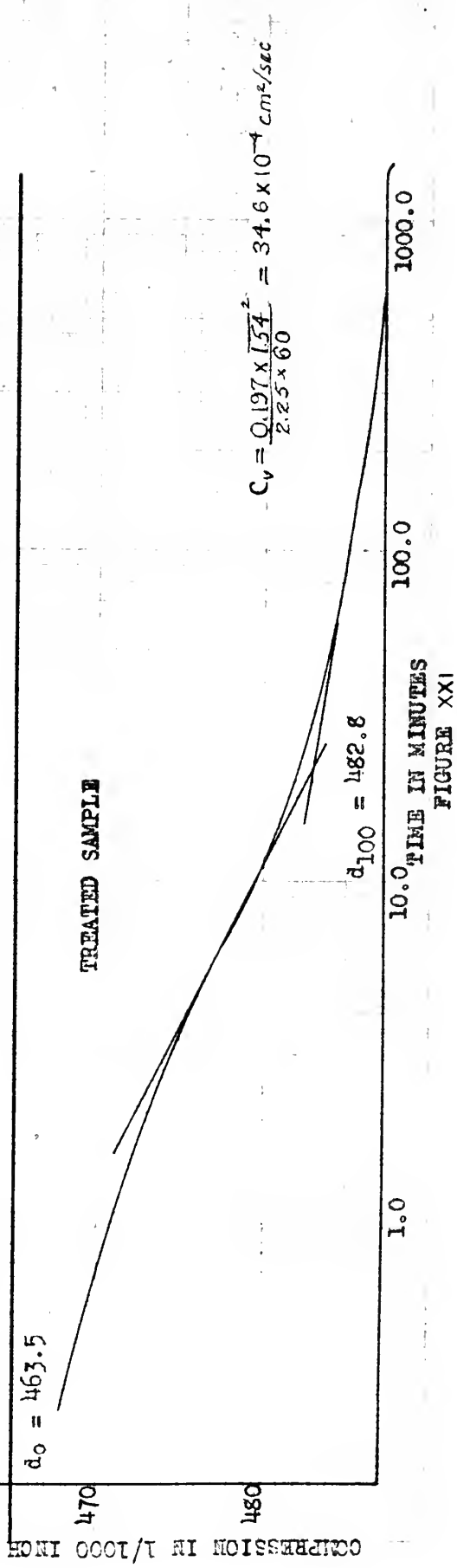
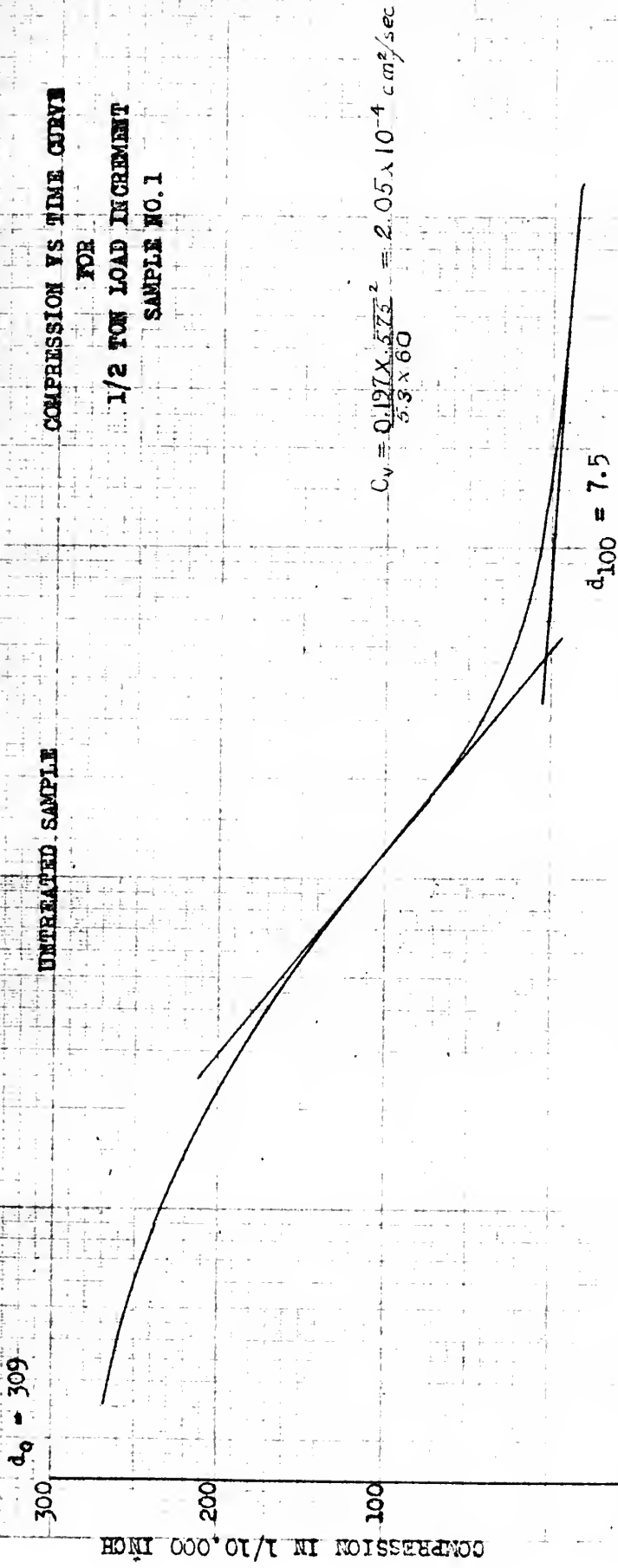


FIGURE XXI

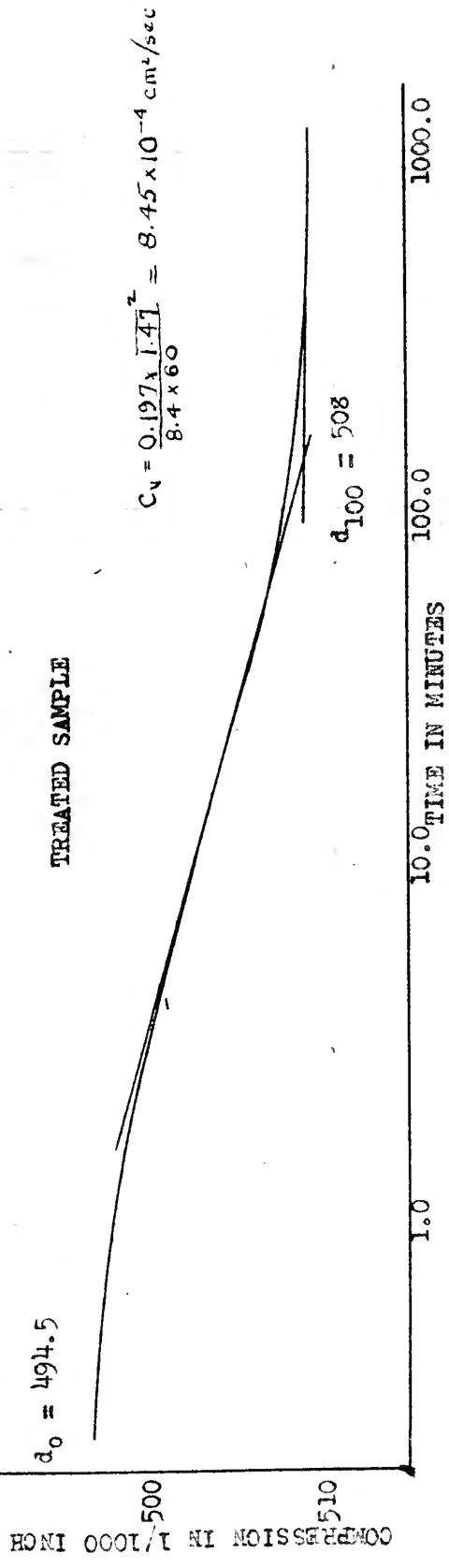
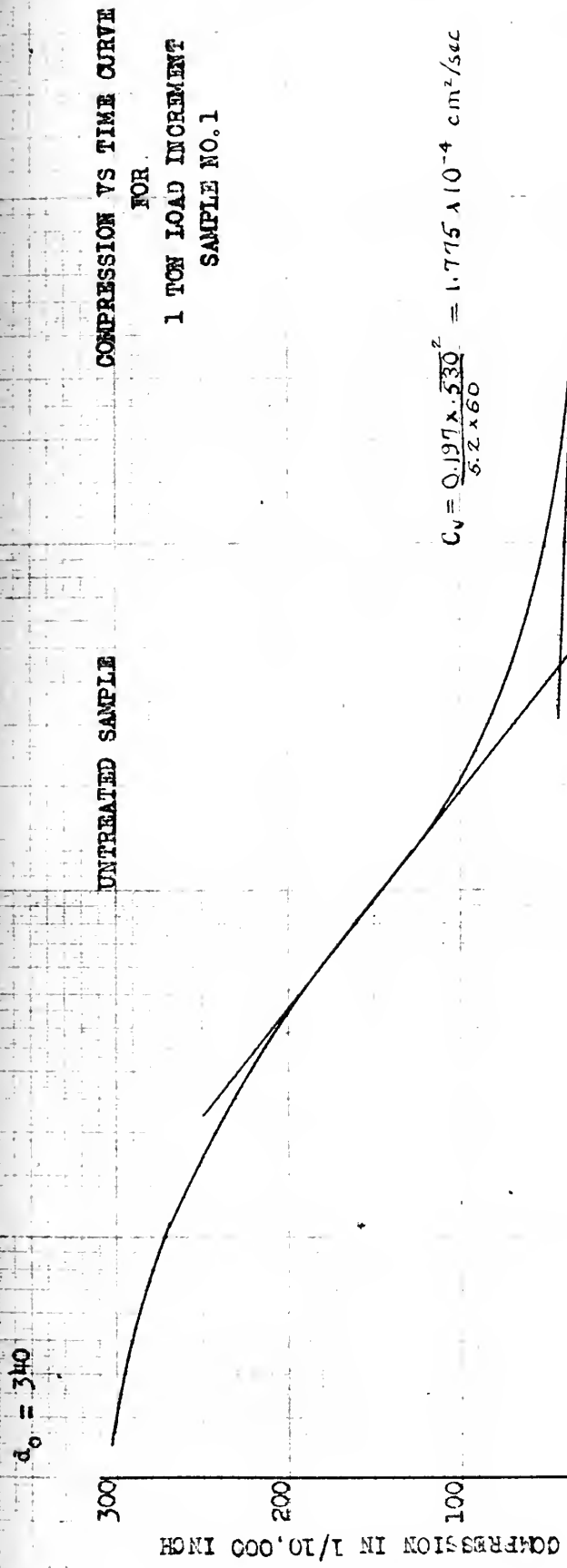


FIGURE XXII

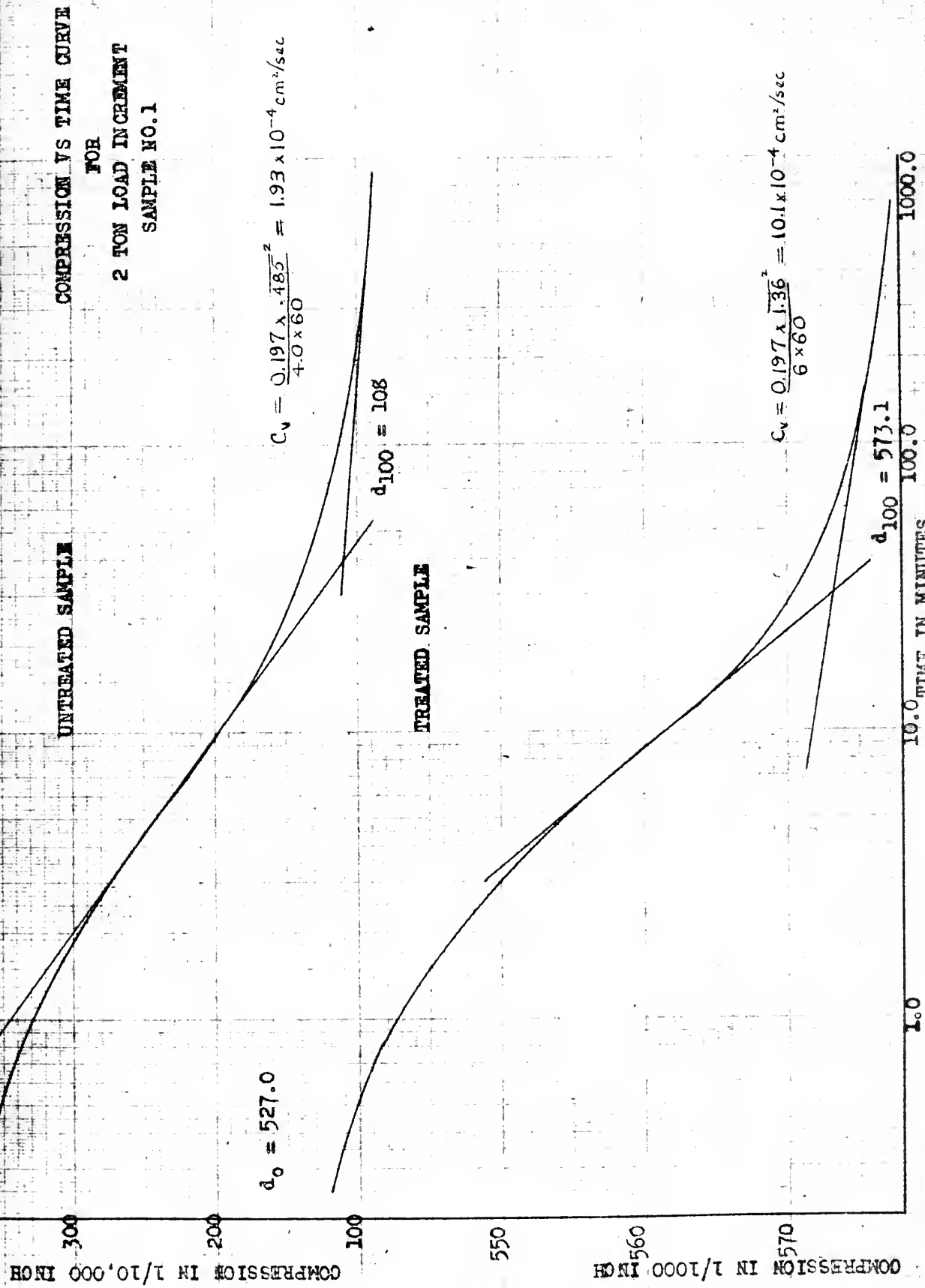


FIGURE XXIII

COMPRESSION IN 1/10,000 INCH

COMPRESSION IN 1/1000 INCH

UNTREATED SAMPLE

COMPRESSION VS TIME CURVE

FOR

4 TON LOAD INCREMENT

SAMPLE NO. 1

$d_0 = 596.1$

$$C_v = \frac{0.197 \times 1.444^2}{3.4 \times 60} = 1.90 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$d_{100} = 110.5$

TREATED SAMPLE

$$C_v = \frac{0.197 \times 1.195^2}{8.5 \times 60} = 5.52 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$d_{100} = 626.4$

1.0

10.0

100.0

1000.0

TIME IN MINUTES

FIGURE XXIV

readings for the treated sample curves subjected to the smaller load increments because the initial segment of the curve was a very flat curve. This difficulty probably resulted in some inaccuracies in the determination of the t_{50} factor used in computing the coefficient of consolidation. It would probably have been wise to use the square root fitting method on those soils exhibiting so much secondary compression that the logarithmic plot did not produce a characteristic shape.

Figure XXV represents the void ratio versus load curves for sample number 1. It is interesting to note that under each load increment the void ratio of the treated sample was less than that of the untreated sample. This means that there was less consolidation under load for the treated sample than for the untreated sample. It was also noted that the difference in void ratio was becoming increasingly less as the size of load increments and duration of electrical potential increased.

Figure XXXV presents a comparison of the coefficients of consolidation for the treated and untreated samples used in test number 1. One questionable assumption was made in order that the coefficients of consolidation could be calculated. This assumption was that during consolidation the treated sample was subjected to single drainage only.

As indicated in the "Theory" section, several

VOID RATIO VS LOAD CURVES

FOR

SAMPLE NO. 1

A. TREATED SAMPLE

B. UNTREATED SAMPLE

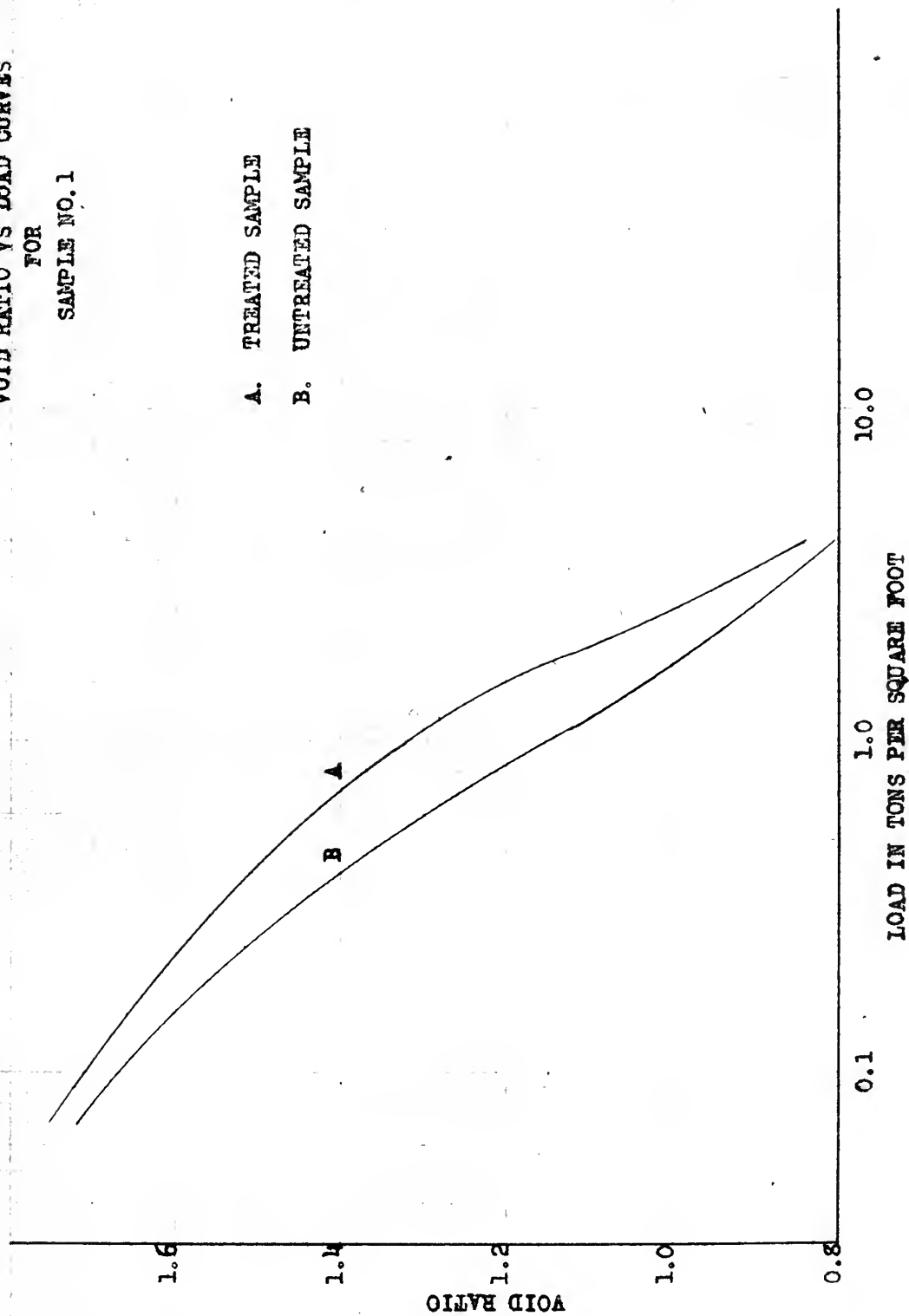


FIGURE XXV



investigators have discovered that during the first minutes of a test there is some drainage through both the anode and cathode plates and after that period the flow is primarily through the cathode plate. But as discussed previously, there can be definite oscillations in the direction of flow of water in the sample and under certain conditions complete reversal of flow direction can occur. The magnitude of these variations and their effect on the above assumption are not known.

An attempt to determine the direction of flow of water in the treated sample was made by placing a small quantity of methyl orange on the anode face of the soil sample used in test number 2. However, due to the initial anode drainage, most of the dye was expelled into the liquid on the anode side of the electro-osmometer. There was not a visible trace of dye on the cathode side of the apparatus.

C. Test Number 2.

The consolidation curves in Figures XXVI, XXVII, XXVIII, XXIX and XXX represent the results obtained from test number 2. From Figures XXVI and XXVII it can be seen that the treated sample consolidation curves are not characteristic and there is a strong indication that these curves represent the secondary consolidation phase of these load increments. For each load increment of this test, the treated sample reached the theoretical one hundred percent

COMPRESSION IN 1/10,000 INCH

COMPRESSION IN 1/1000 INCH

UNTREATED SAMPLE

TREATED SAMPLE

COMPRESSION VS TIME CURVE
FOR
1/4 TON LOAD INCREMENT
SAMPLE NO.2

1.0 10.0 100.0 1000.0

TIME IN MINUTES

FIGURE XXVI

COMPRESSION IN 1/10,000 INCH

COMPRESSION IN 1/1000 INCH

UNTREATED SAMPLE

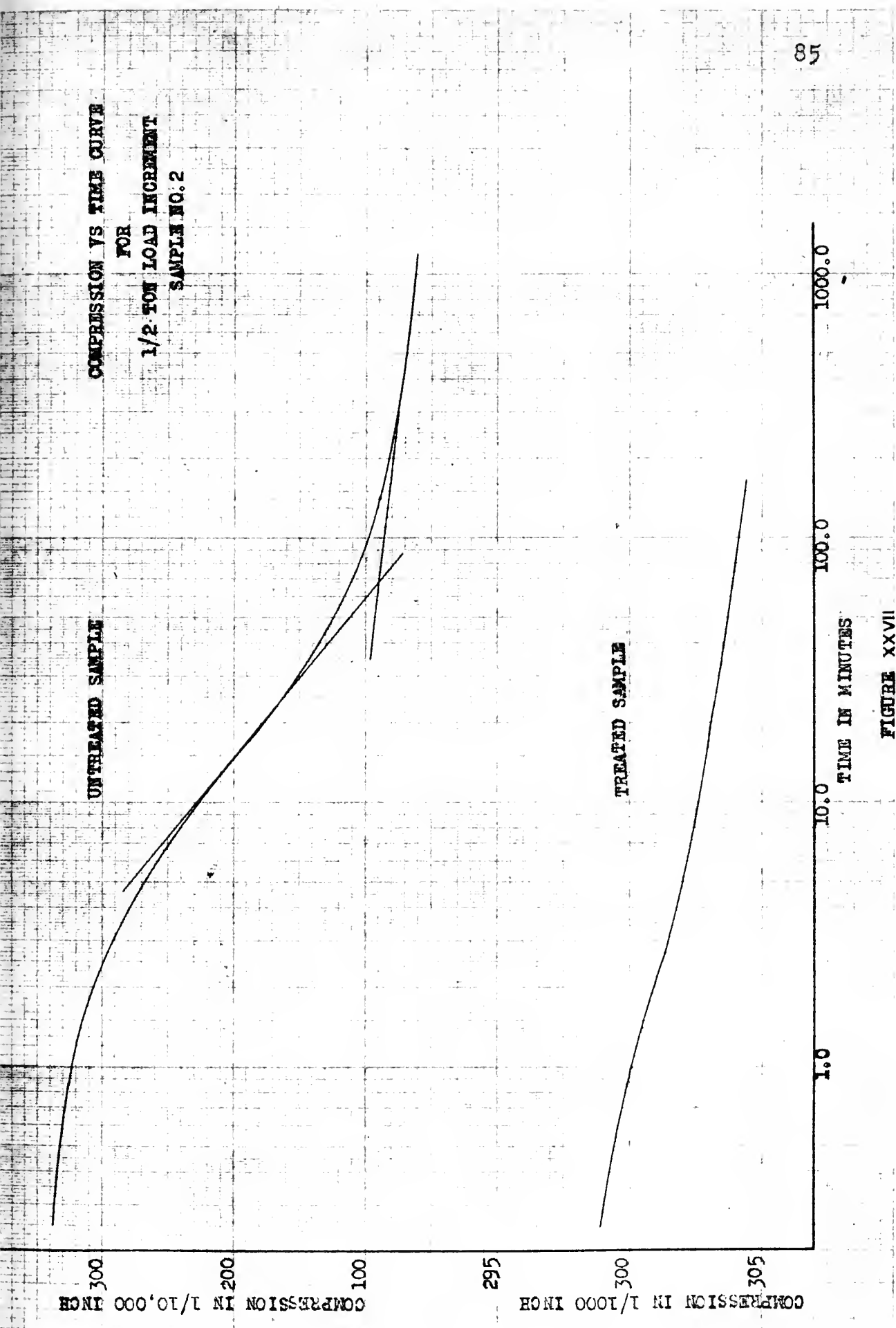
TREATED SAMPLE

COMPRESSION VS TIME CURVE
FOR
1/2 TON LOAD INCREMENT
SAMPLE NO. 2

1.0 10.0 100.0 1000.0

TIME IN MINUTES

FIGURE XXVII



COMPRESSION VS TIME CURVE
FOR
1 TON LOAD INCREMENT
SAMPLE NO.2

UNTREATED SAMPLE

TREATED SAMPLE

$$d_0 = 1452$$

$$d_0 = 309.5$$

$$C_v = \frac{0.197 \times 580^2}{7.7 \times 60} = 1.43 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$d_{100} = 150$$

$$C_v = \frac{0.197 \times 1325^2}{4.5 \times 60} = 128 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$d_{100} = 328$$

COMPRESSION IN 1/10,000 INCH

COMPRESSION IN 1/1000 INCH

TIME IN MINUTES

FIGURE XXVIII

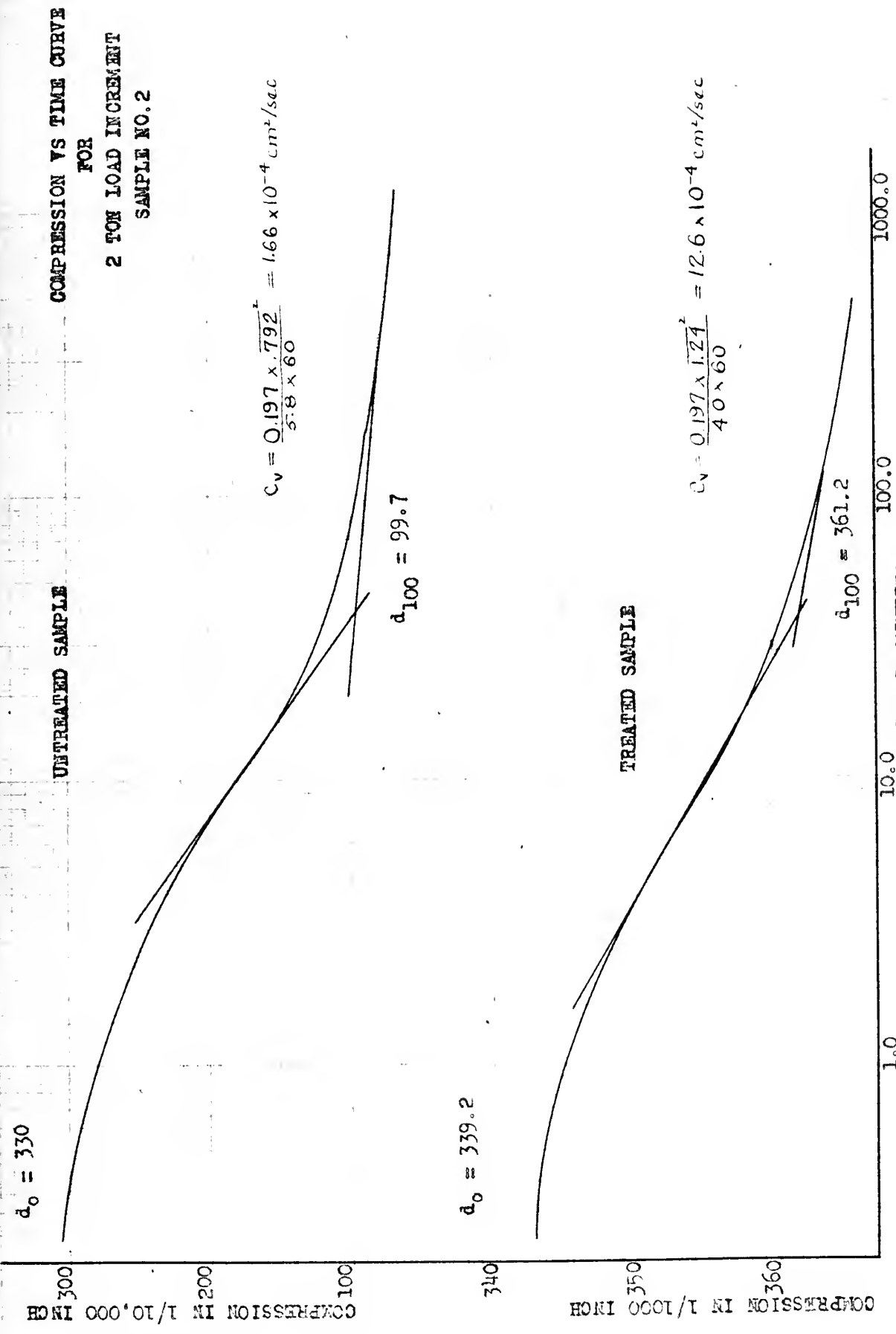


FIGURE XXIX

COMPRESSION VS TIME CURVE

FOR

4 TON LOAD INCREMENT

SAMPLE NO.2

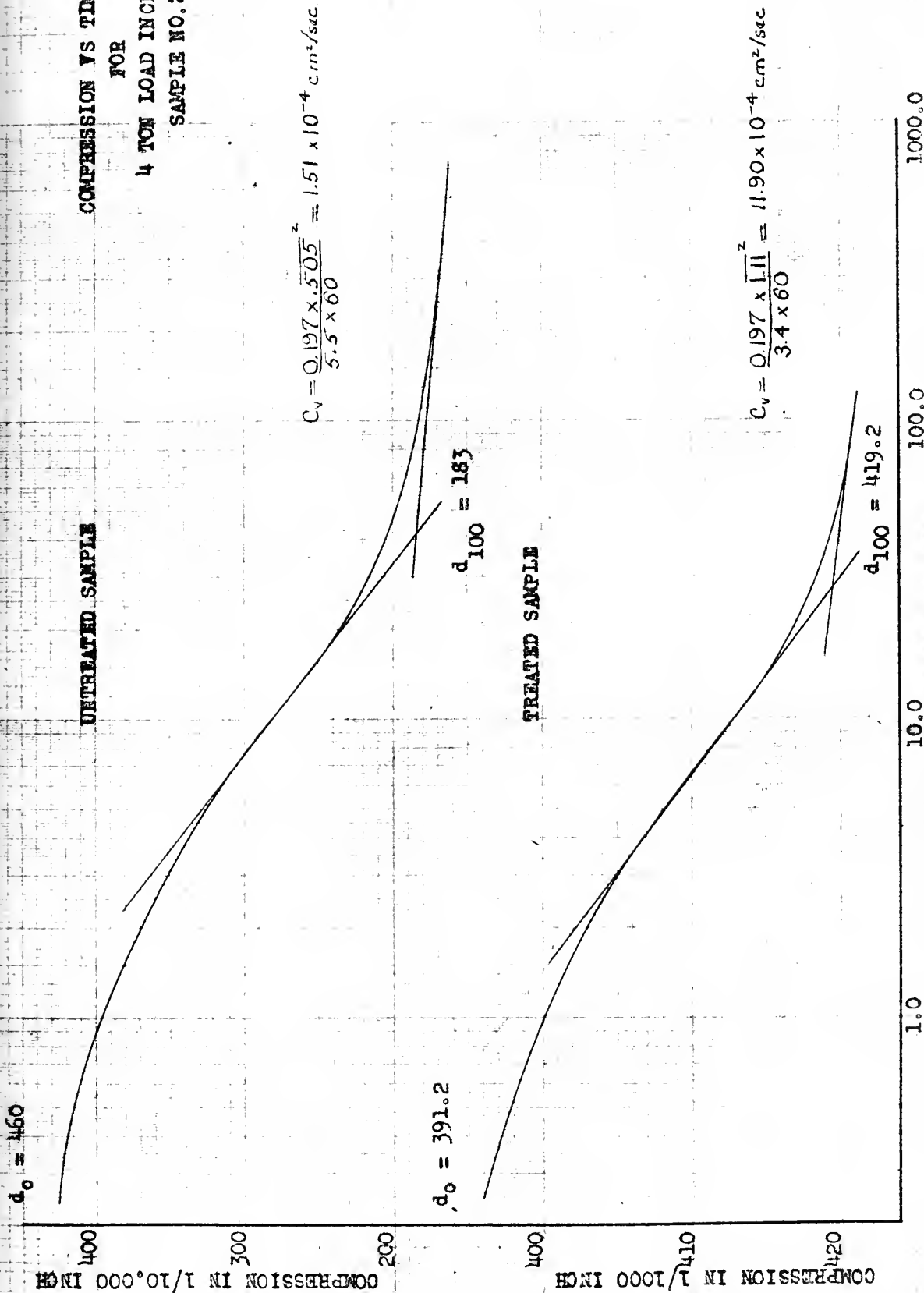


FIGURE XXX

consolidation point in a shorter time than did the untreated sample, however, for the heavier load increments and longer duration of application of electrical potential the difference in consolidation time was relatively small.

The void ratio versus load curves Figure XXXI, for this test were similar to those obtained in test number 1, except that the relative positions of the curves for the treated and untreated samples were further apart for test number 2 than for test number 1. This is believed due to the presence of the methyl orange in this test. Since methyl orange in solution produces sodium ions it can be seen from Winterkorn's (20) observations that these curves could possibly have greater relative displacement than would occur if sodium ions were not present.

Although only three values were obtained for the untreated and treated samples the coefficient of consolidation curves shown in Figure XXXV were similar to those obtained for test number 1. There was a greater displacement between the curves plotted from the results of test number 1 during periods that the $1/4$ and $1/2$ ton per square foot increments were applied than between the curves obtained for test number 2. However, at the one ton per square foot increment the displacement for both tests were approximately equal. For larger load increments the displacements between the applicable curve segments obtained for test number 1 was less than those obtained in test

VOID RATIO VS LOAD CURVES
FOR
SAMPLE NO. 2

- A. TREATED SAMPLE
- B. UNTREATED SAMPLE

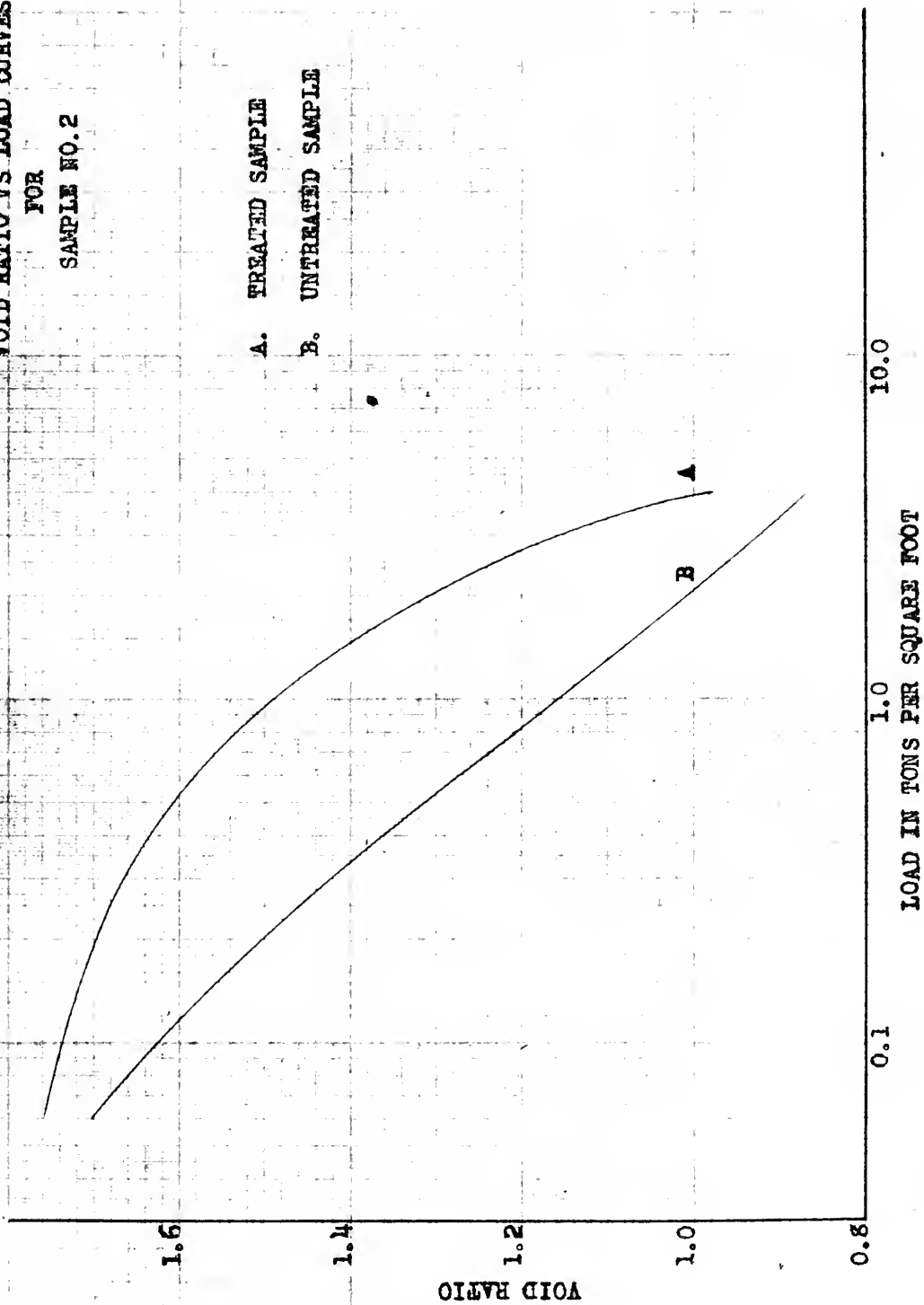


FIGURE XXXI

number 2.

D. Test Numbers 3 and 4

As indicated before test numbers 3 and 4 were conducted primarily for permeability determinations. These samples were pre-loaded to 1/4 ton per square foot and consolidated under this load before the application of an electrical potential. Figure XXXII indicates the deflections noted in the sample after the samples were subjected to an electrical potential. It is interesting to note that after the electrical potential had been applied for some time the sample began to expand. This expansion is probably due to any one or a combination of the following factors: 1. a reversal of electro-osmotic flow; 2. the attempt of the clay to form a new structure, or 3. the addition of foreign material to the soil sample.

E. Test Number 5

The consolidation curves shown in Figures XXXIII, XXXIV, XXXV, XXXVI and XXXVII represent the results obtained from test number 5. The results of test number 5 are considered to be the most accurate of test numbers 1, 2 and 5. These tests were all conducted under practically the same modifications in technique and procedure determined necessary by conducting test numbers 1 and 2. It was noted that for the consolidation under the load increments of 1/4, 1/2 and 1 ton per square foot it required a longer period of time to

COMPRESSION VS TIME CURVE
FOR
SAMPLE NO. 3



COMPRESSION VS TIME CURVE
FOR
SAMPLE NO. 4



500

600

700

800

900

COMPRESSION IN 1/1000 INCH

1.0

10.0

100.0

1000.0

TIME IN MINUTES

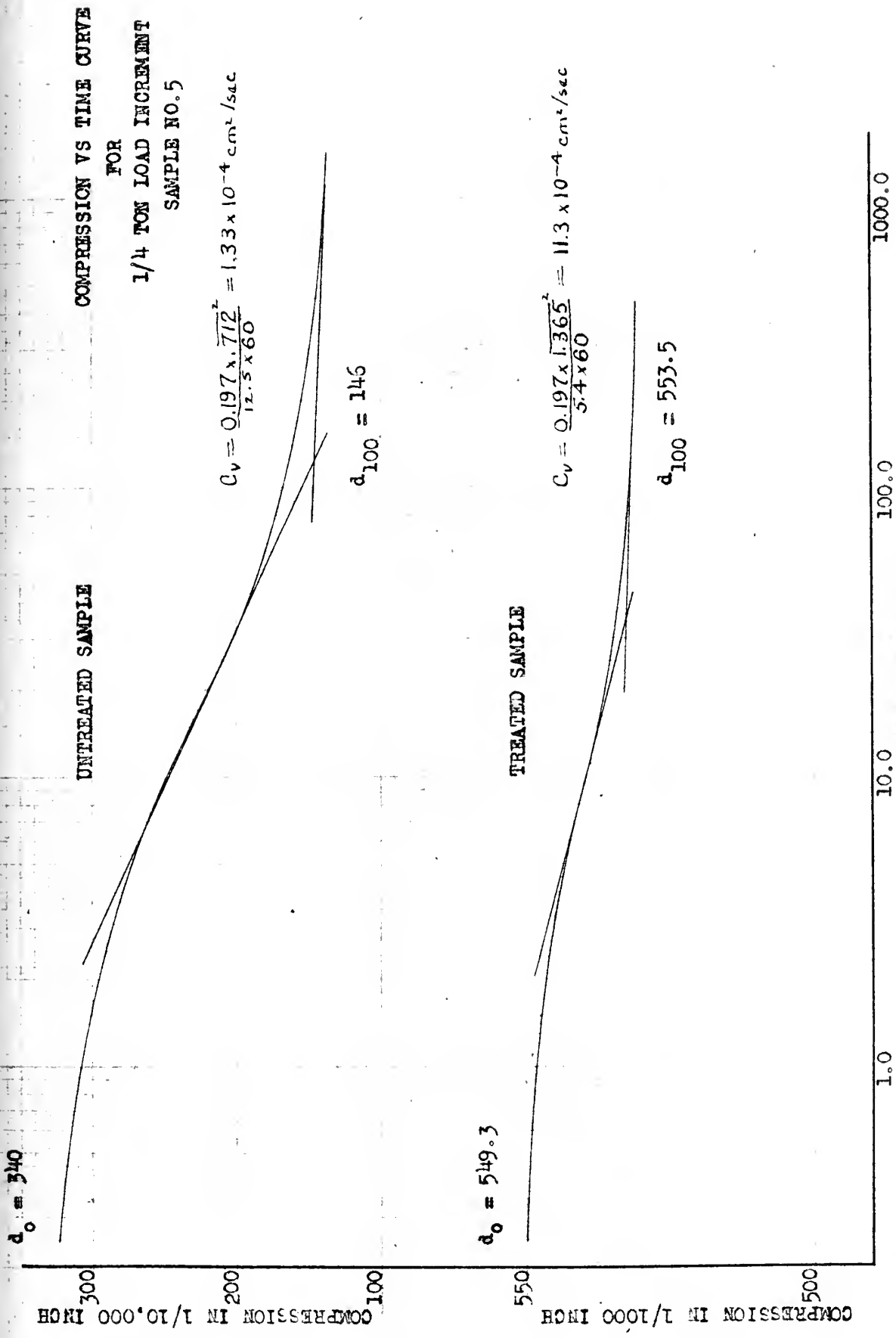
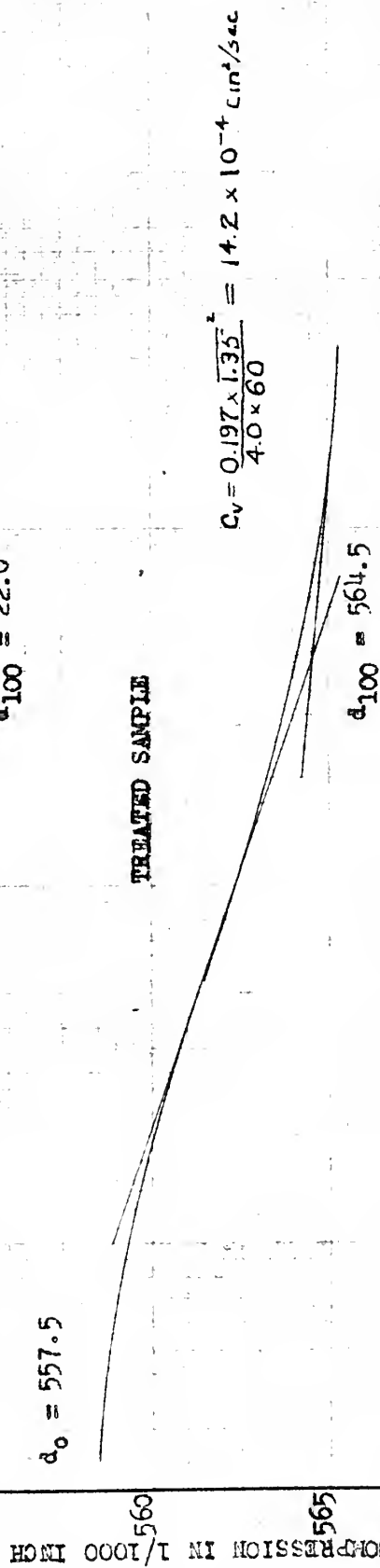


FIGURE XXXIII



TIME IN MINUTES

FIGURE XXXIV

90 = 210

COMPRESSION IN 1/10,000 INCH

UNTREATED SAMPLE

COMPRESSION VS TIME CURVE

FOR
1 TON LOAD INCREMENT
SAMPLE NO. 5

$d_0 = 571.4$

$$C_v = \frac{0.197 \times \sqrt{635}}{7.6 \times 60} = 1.74 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$d_{100} = 42.0$

TREATED SAMPLE

COMPRESSION IN 1/1000 INCH

$$C_v = \frac{0.197 \times \sqrt{1.27}}{5.6 \times 60} = 9.45 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$d_{100} = 585.05$

1.0

10.0

TIME IN MINUTES

100.0

1000.0

FIGURE XXXV

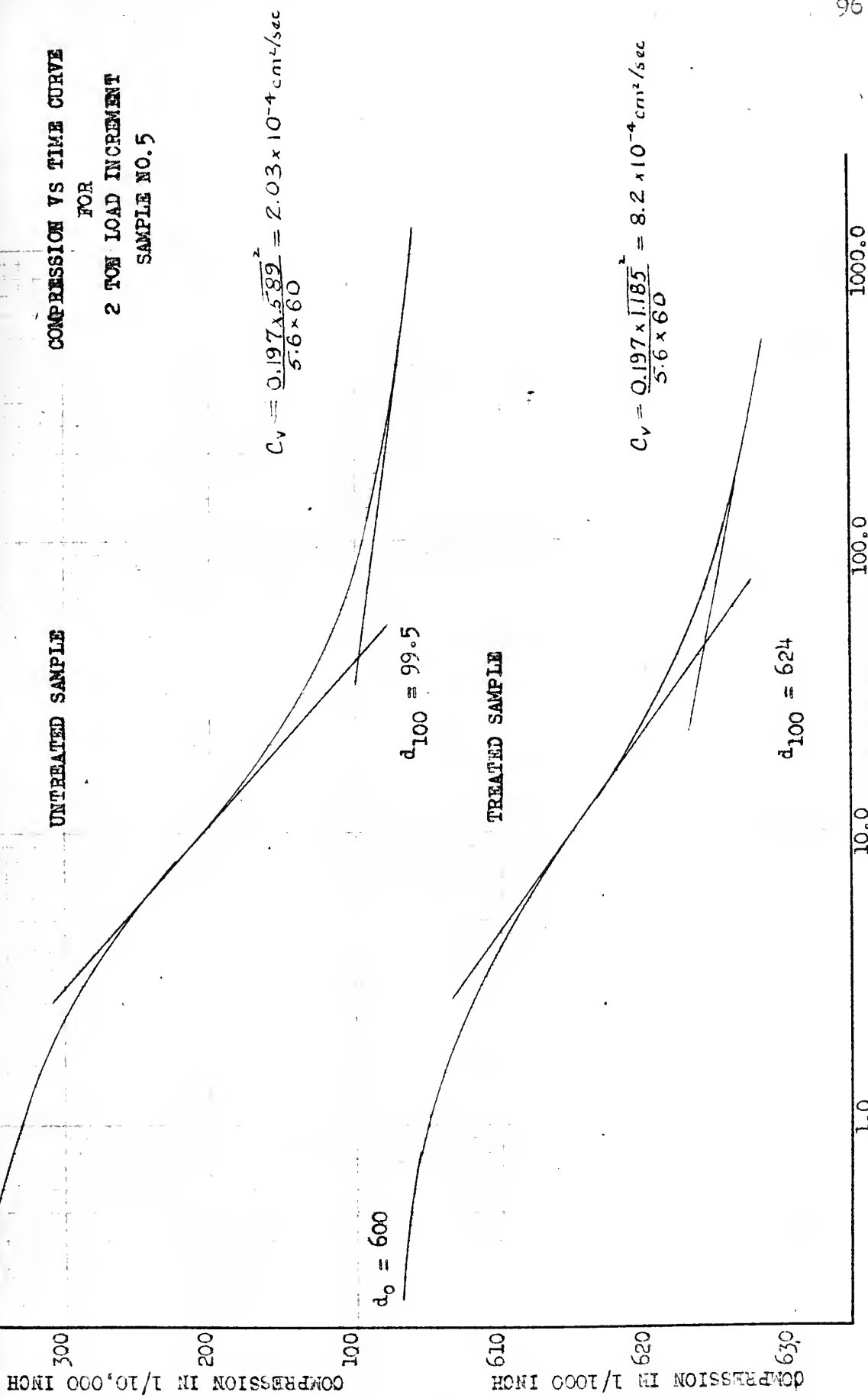


FIGURE XXXVI

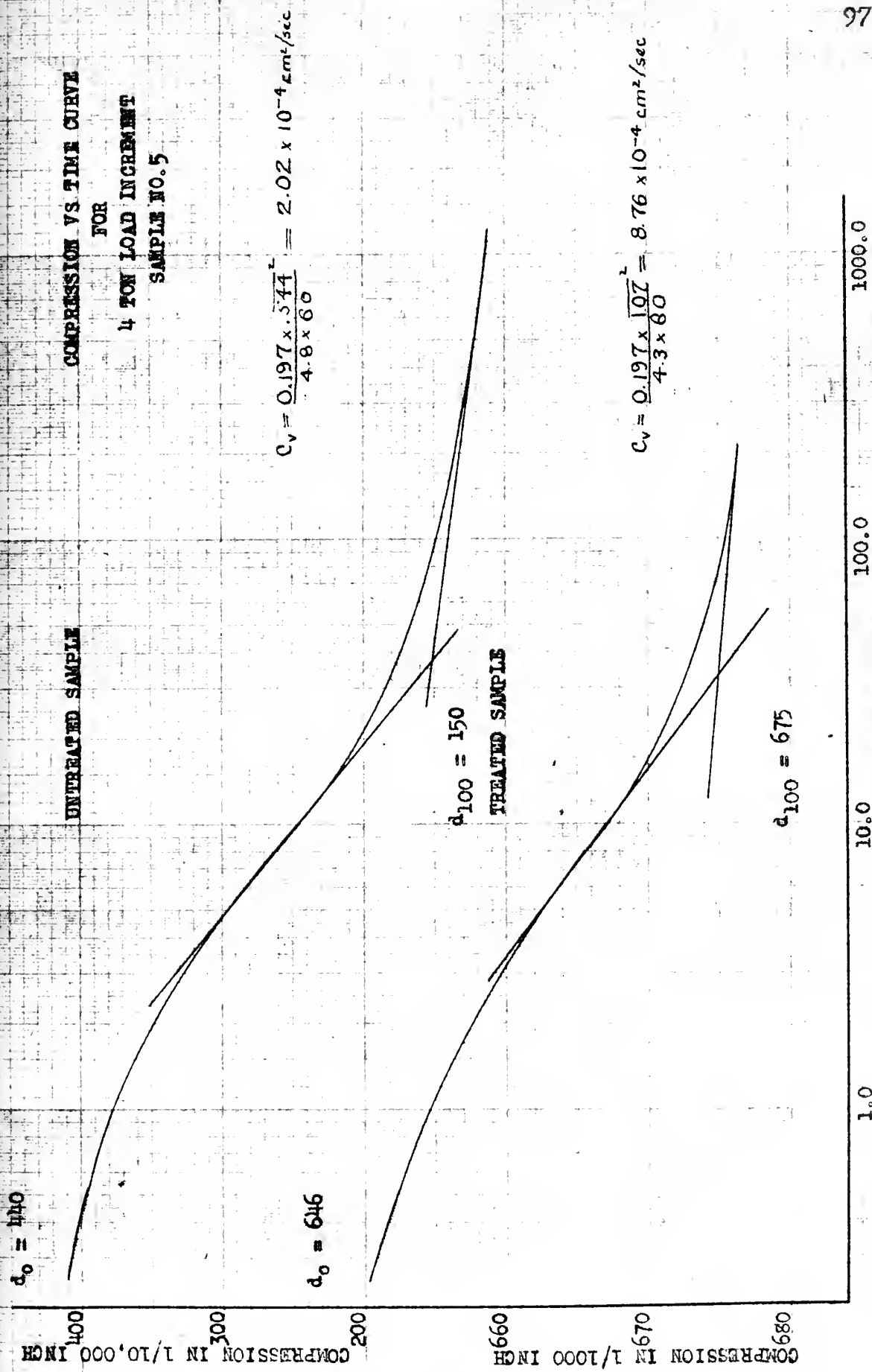


FIGURE XXXVII

100
100
100

100
100
100
100
100
100
100
100
100
100

100
100

100
100
100

100
100

reach the theoretical point of one hundred percent consolidation for the untreated sample than it did for the treated sample, however, for consolidation under the 2 and 4 tons per square foot load increments just the reverse was true.

As shown in Figure XXXVIII, the void ratio versus load curves are similar to those obtained in test numbers 1 and 2, except for the fact that their relative positions are different. In this test the curve for the untreated sample crosses and recrosses the curve for the treated sample which indicates that for the one and two tons per square foot load increments the treated sample was attaining a slightly lower void ratio value than the untreated sample. This condition was not observed in the results of test numbers 1 and 2.

The coefficient of consolidation curves in Figure XXXXVI, for sample number 5 appeared to be an average of the results obtained for test numbers 1 and 2.

F. Test Number 6

As mentioned before, test number 6 was conducted primarily to determine the effects that the time consumed in electrical permeability determinations might have had on test numbers 1, 2 and 5.

The consolidation curves in Figures XXXIX, XXXX, XXXXI, XXXXII and XXXXIII represent the results of test number 6.

The first difference noted between this test and

VOID RATIO VS LOAD CURVES

FOR

SAMPLE NO. 5

A. TREATED SAMPLE

B. UNTREATED SAMPLE

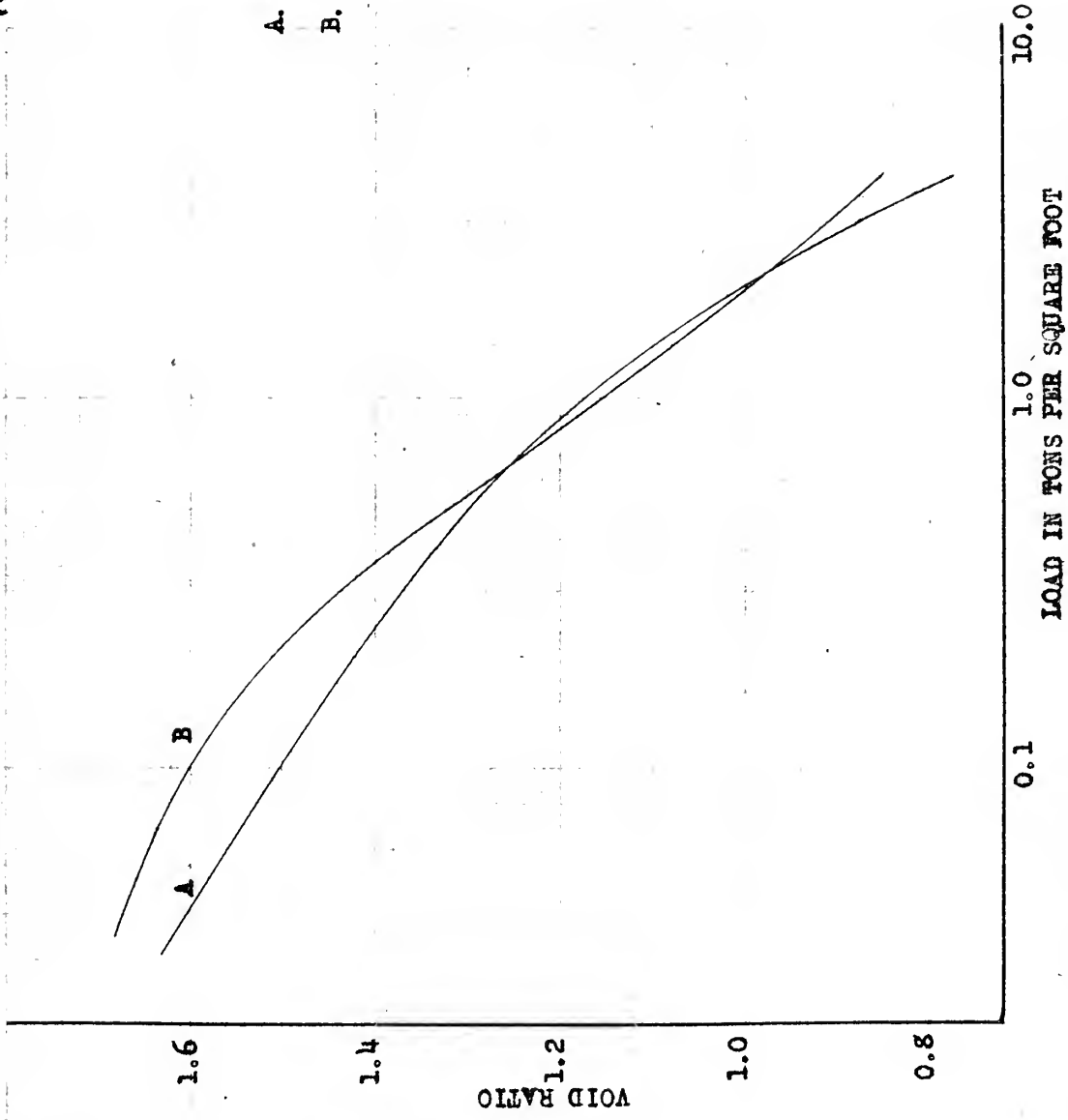


FIGURE XXXVIII

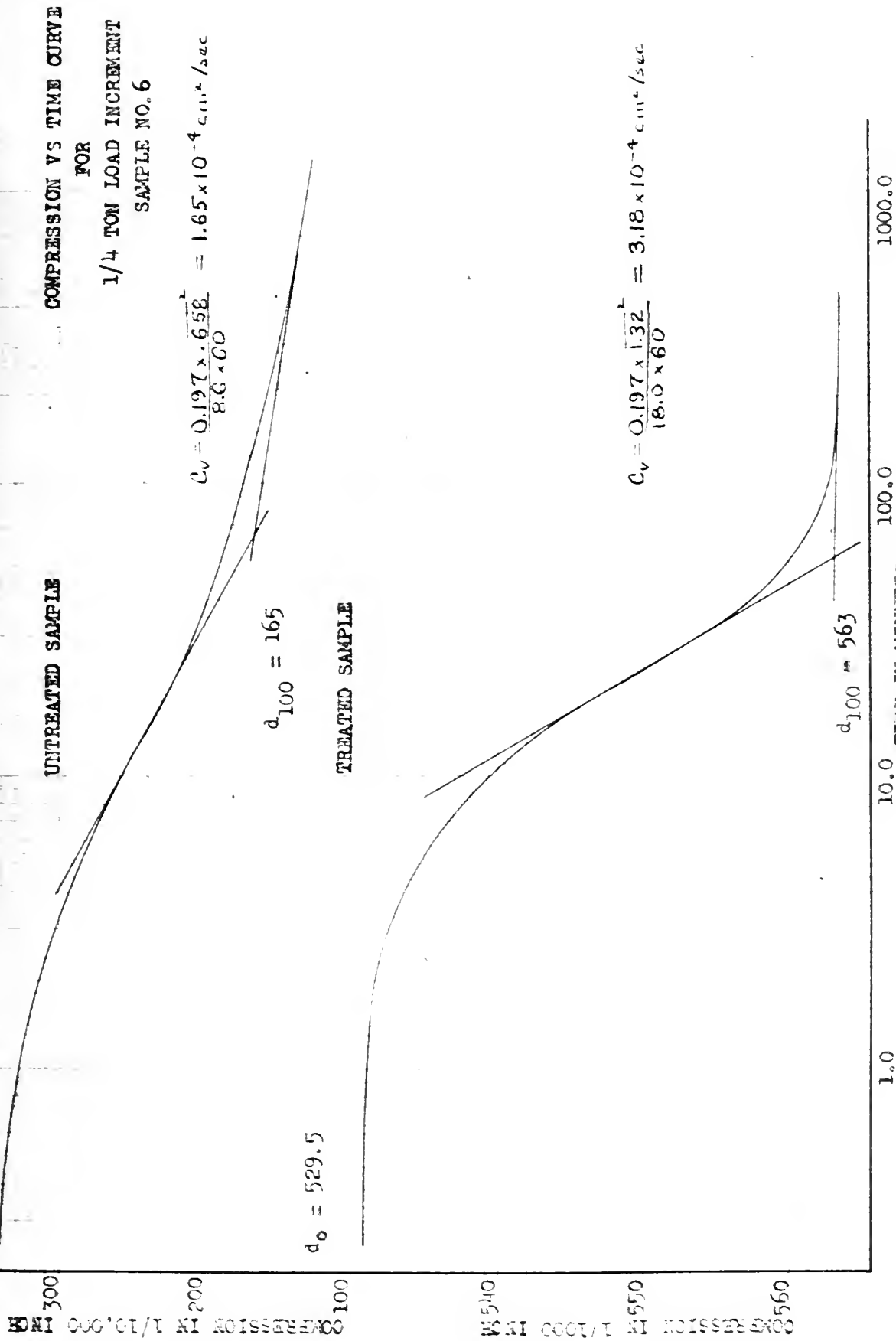


FIGURE XXXIX

COMPRESSION VS TIME CURVE
FOR
1/2 TON LOAD INCREMENT
SAMPLE NO. 6

UNTREATED SAMPLE

$d_0 = 300$

$$C_v = \frac{0.197 \times \frac{626}{11.0 \times 60}}{1.17 \times 10^{-4} \text{ cm}^2/\text{sec}}$$

$d_{100} = 12$

TREATED SAMPLE

$d_0 = 563.9$

$$C_v = \frac{0.197 \times \frac{1303}{5.2 \times 6.0}}{10.7 \times 10^{-4} \text{ cm}^2/\text{sec}}$$

$d_{100} = 567.9$

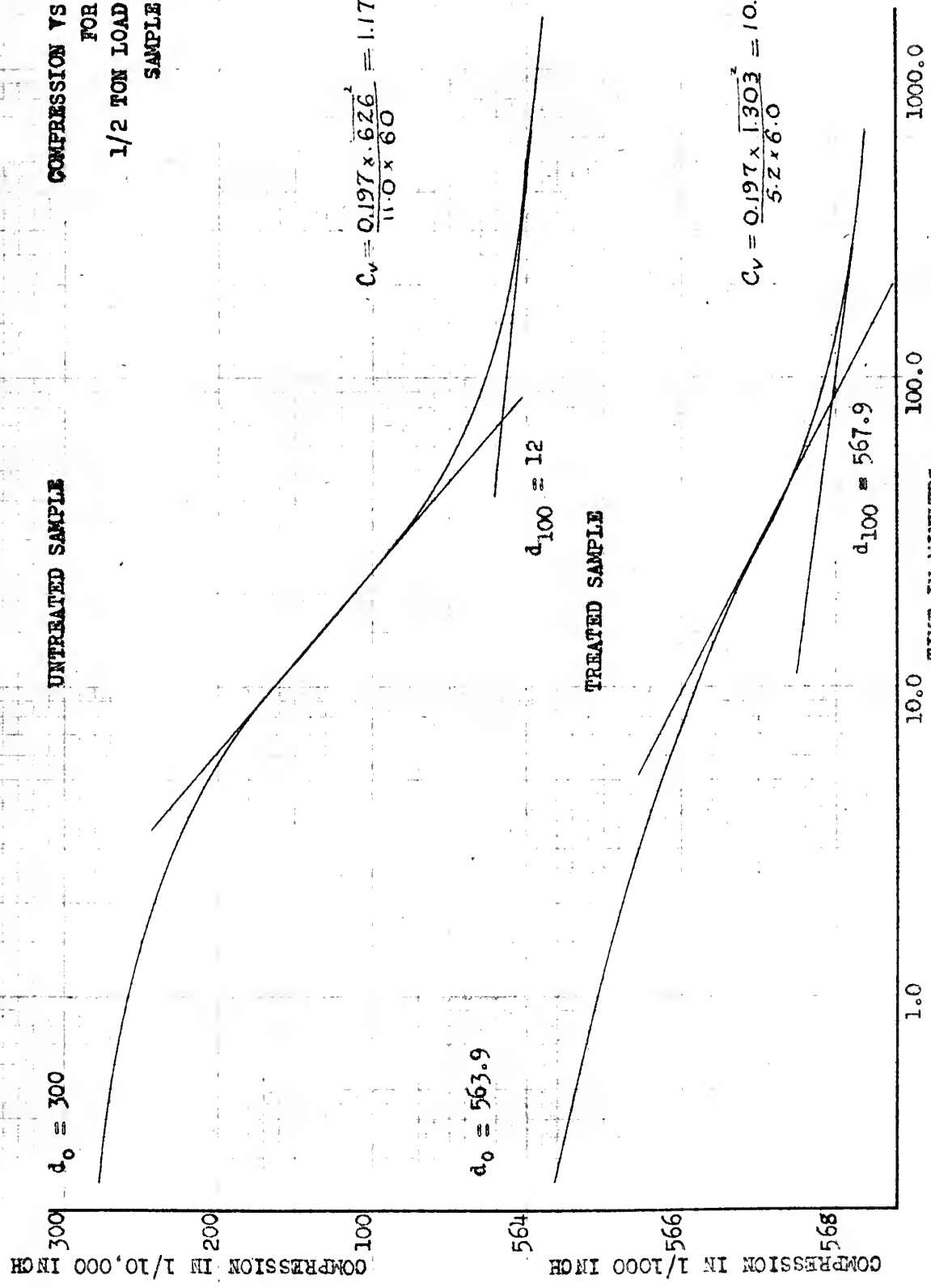


FIGURE XXXX

$d_0 = 359.0$

COMPRESSION IN 1/10,000 INCH

UNTREATED SAMPLE

COMPRESSION VS TIME CURVE

FOR

1 TON LOAD INCREMENT

SAMPLE NO. 6

$$C_v = \frac{0.197 \times \sqrt{.570}}{7.6 \times 60} = 1.40 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$d_0 = 573.4$

$d_{100} = 69.0$

TREATED SAMPLE

$$C_v = \frac{0.197 \times \sqrt{1.255}}{4.4 \times 60} = 12.05 \times 10^{-4} \text{ cm}^2/\text{sec}$$

COMPRESSION IN 1/1000 INCH

$d_{100} = 583.5$

1.0 10.0 100.0 1000.0

TIME IN MINUTES

FIGURE XXXXI

COMPRESSION VS TIME CURVE

FOR

2 TON LOAD INCREMENT

SAMPLE NO. 6

$$C_v = \frac{0.197 \times 525^2}{6.6 \times 60} = 1.37 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$d_o = 594.2$$

$$d_{100} = 122$$

TREATED SAMPLE

$$C_v = \frac{0.197 \times 1.173^2}{6.2 \times 60} = 7.3 \times 10^{-4} \text{ cm}^2/\text{sec}$$

$$d_{100} = 616.2$$

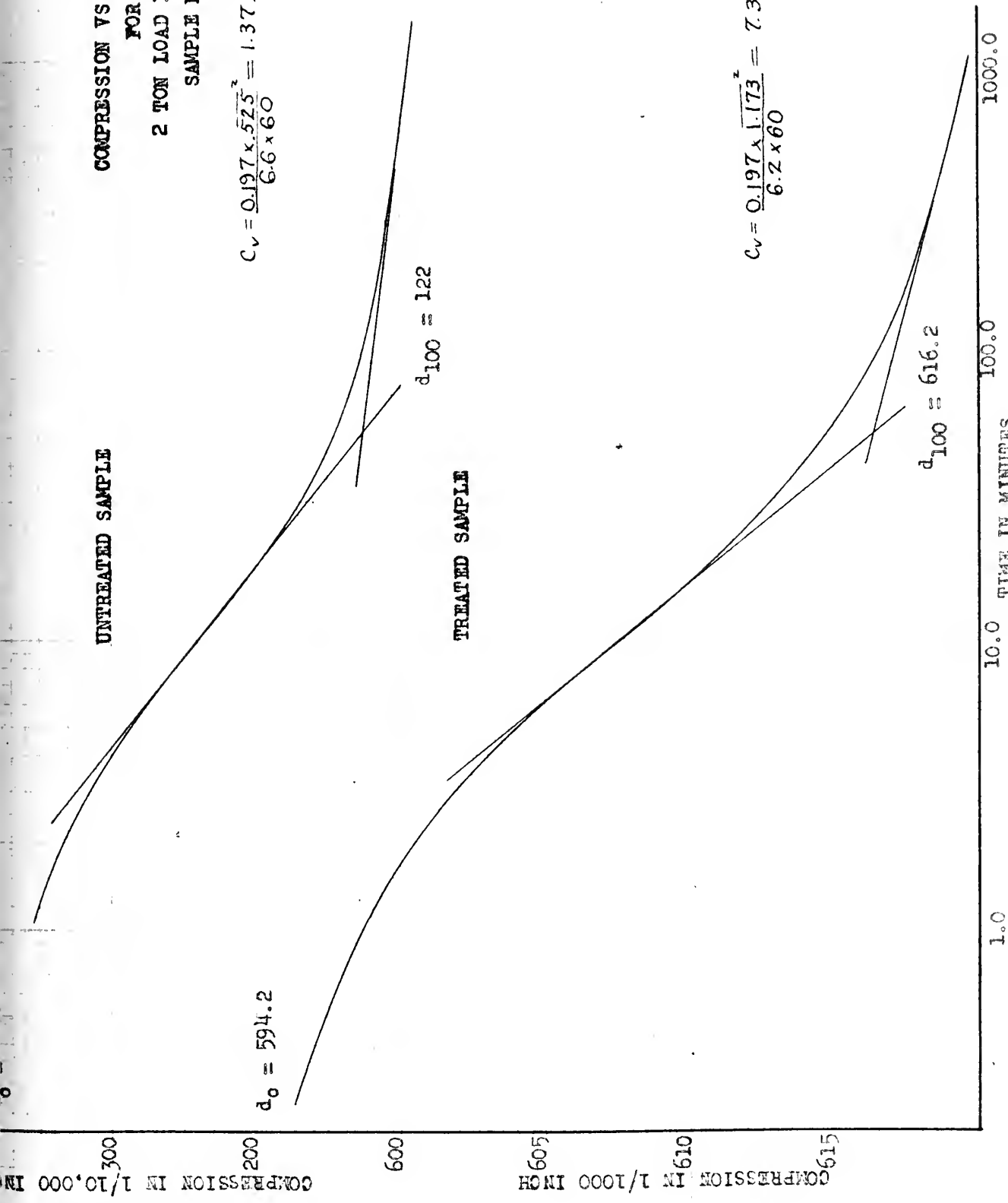


FIGURE XXXXII

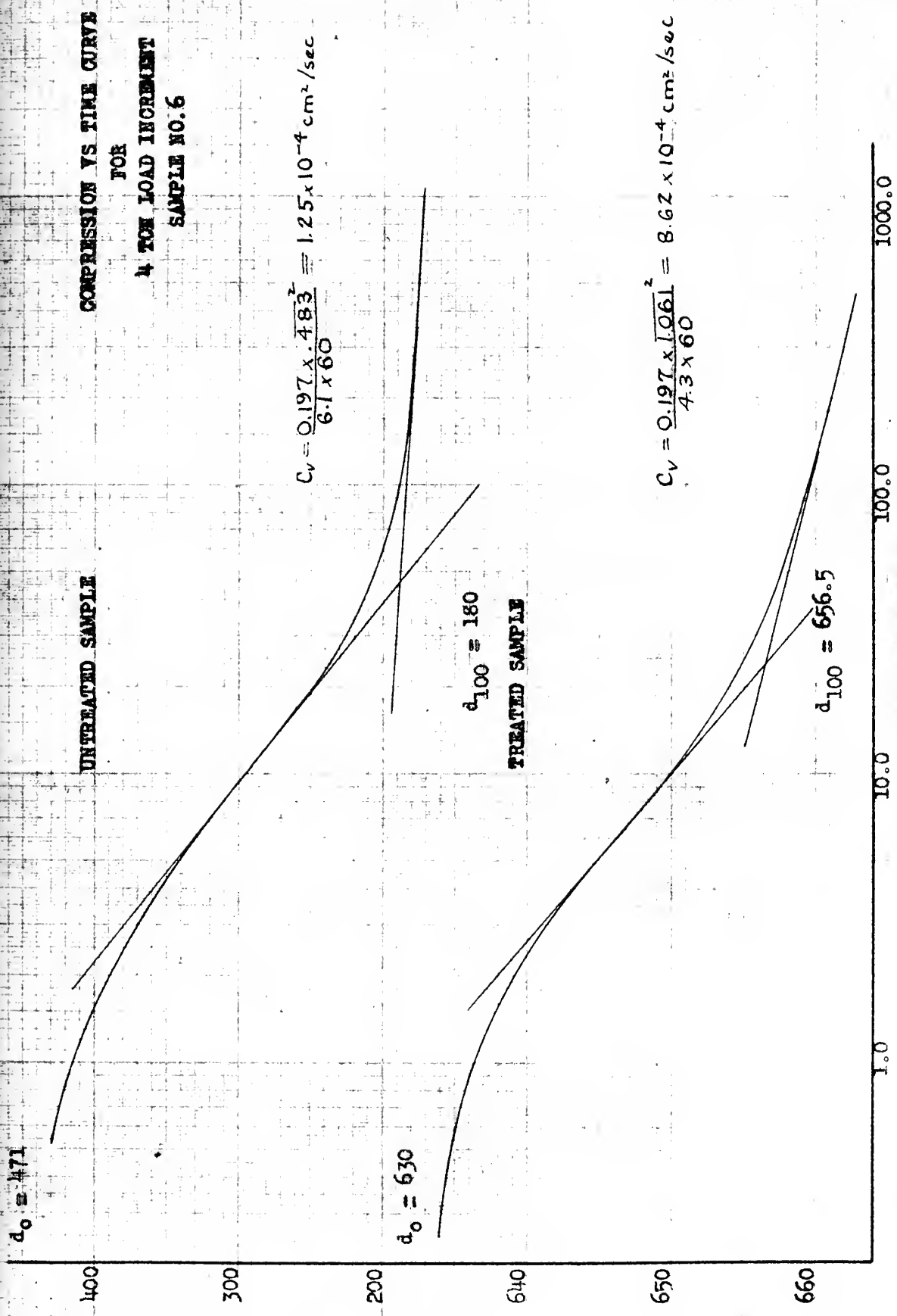


FIGURE XXXXIII

previous tests was the unusually large amount of consolidation obtained under the 1/4 ton per square foot load increment. Except for the 1/2 ton per square foot load increment the treated sample reached the theoretical one hundred percent consolidation point in a shorter time than did the untreated sample.

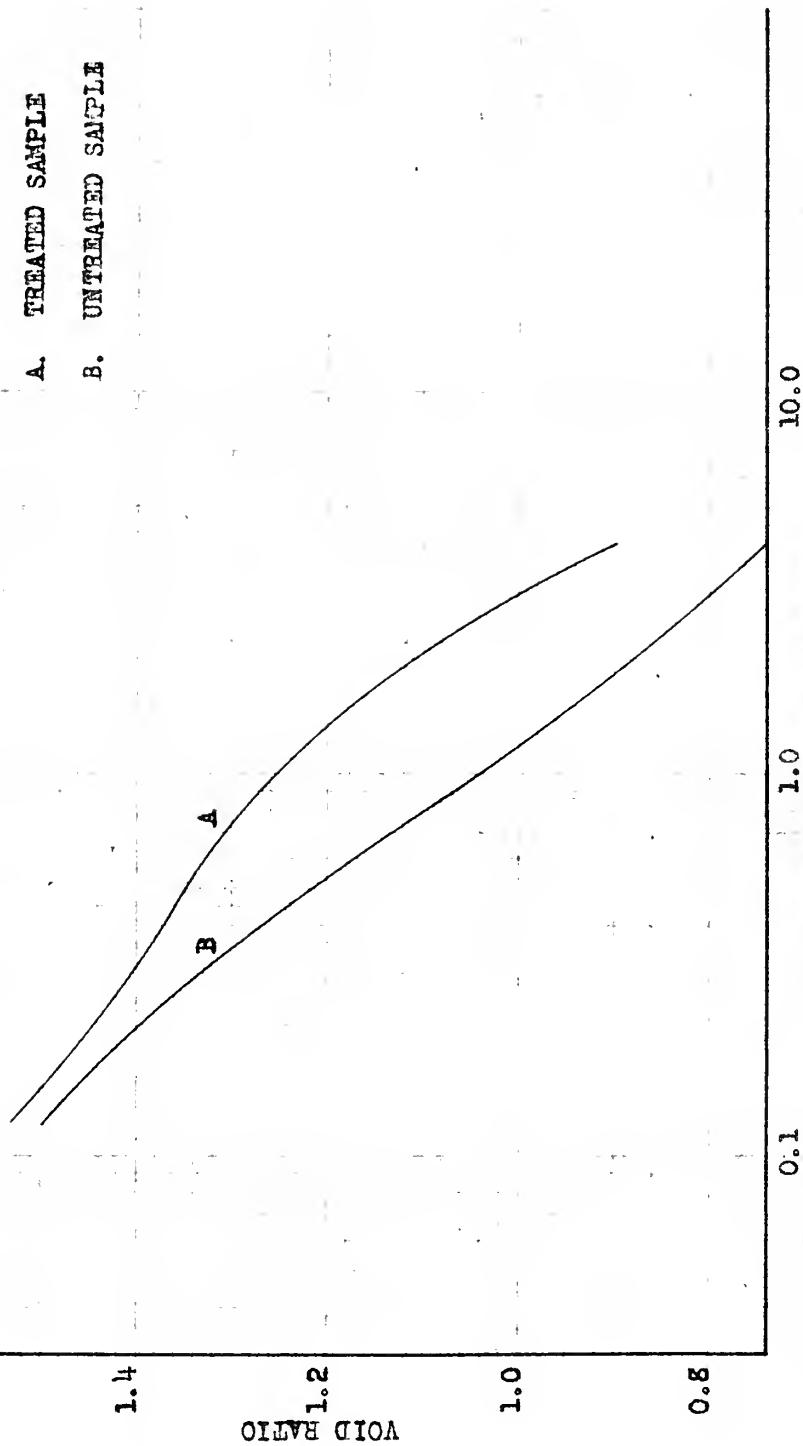
As shown in Figure XXXXIV the void ratio versus load curves are similar to those obtained in test numbers 1 and 2 and seem to strike a very nice average between these tests as far as relative displacement of the curves are concerned.

The most significant difference between test number 6 and test numbers 1, 2 and 5 was that of the shape of the coefficient of consolidation curves as shown in Figure XXXXVI. The coefficient of consolidation curve has undergone a complete reversal in curvature as compared with similar curves for the other tests.

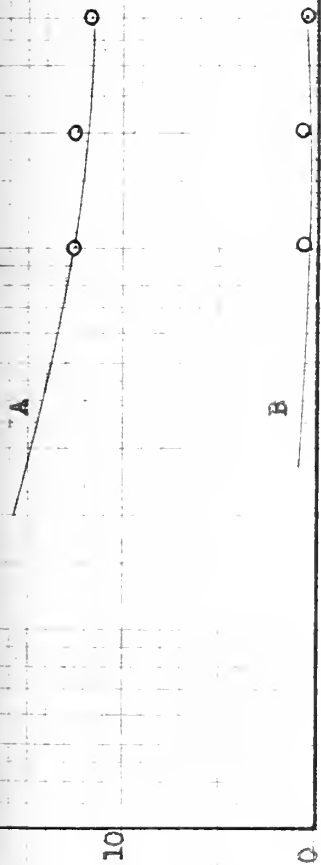
Almost without exception in each series of tests conducted the void ratio attained by the treated sample subjected to a particular load increment was higher than that of the untreated sample subjected to an identical increment. It is the author's opinion that this result displays the results of the phenomenon of electro-chemical hardening discussed in the "Theory Section". The presence of the foreign material in the clay sample and the decomposition of the anode plate tend to indicate base exchange

VOID RATIO VS LOAD CURVES
FOR
SAMPLE NO. 6

- A. TREATED SAMPLE
- B. UNTREATED SAMPLE



COEFFICIENT OF CONSOLIDATION VERSUS LOAD CURVES
FOR
SAMPLE NO. 2



COEFFICIENT OF CONSOLIDATION VERSUS LOAD CURVES
FOR
SAMPLE NO. 1

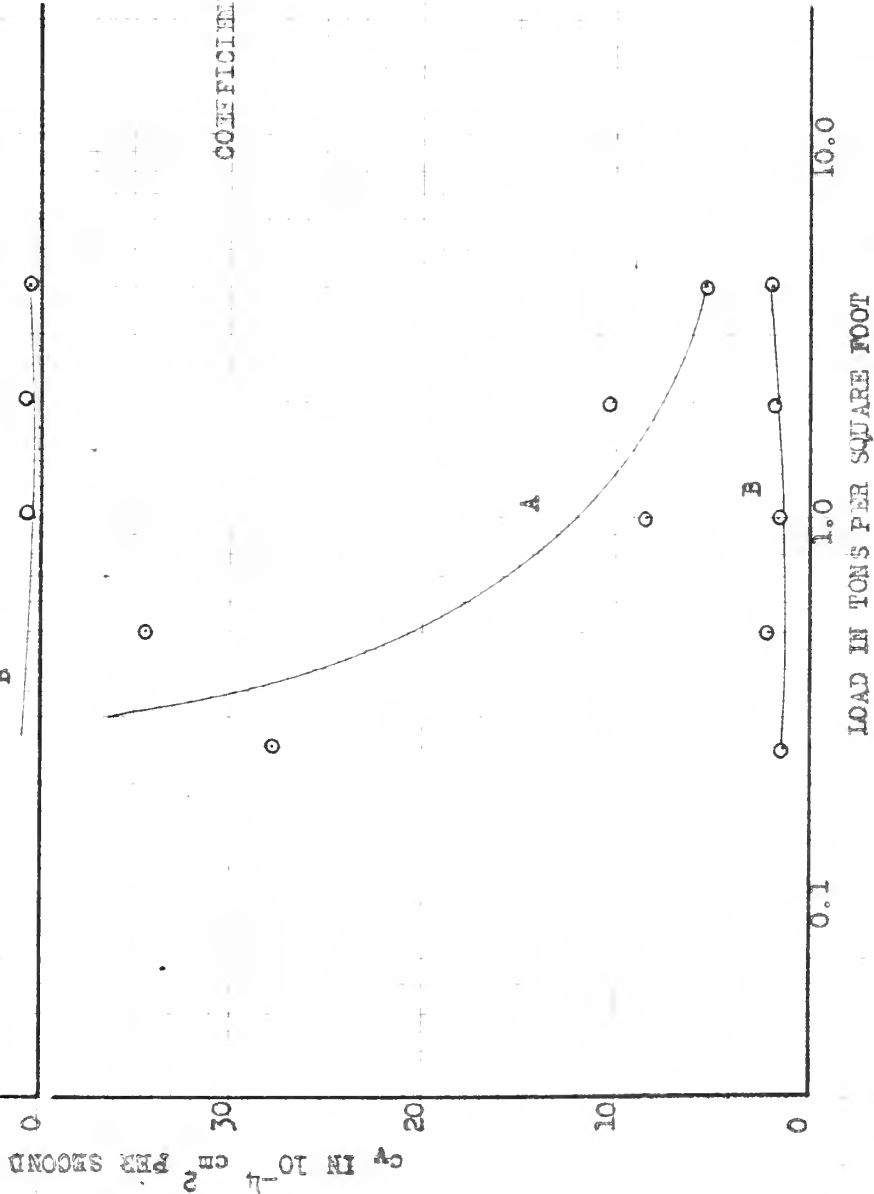
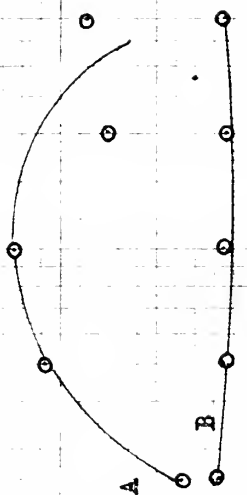


FIGURE XXXXV

COEFFICIENT OF CONSOLIDATION VERSUS LOAD CURVES
FOR
SAMPLE NO. 6



COEFFICIENT OF CONSOLIDATION VERSUS LOAD CURVES
FOR
SAMPLE NO. 5

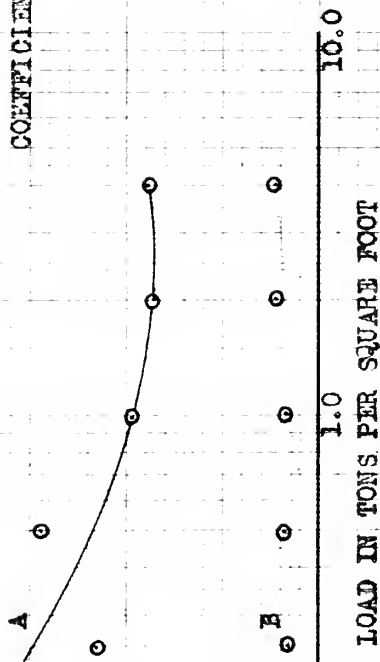


FIGURE XXXXVI

activity must have been considerable. The effect of this action on the clay structure seemed to be one that introduced a certain amount of fixity in the soil structure which tends to resist compression to such a degree that the sample becomes consolidated at a higher void ratio than the untreated sample.

From test numbers 3 and 4 it was observed that if a soil sample, initially consolidated under a particular load increment, was subjected to electrical potential, additional compression of the sample resulted. This fact appears to verify the belief that the reason for the void ratio of the treated sample being higher than that of the untreated sample was due to the phenomenon of electrochemical hardening.

In general, the tests conducted seemed to indicate that when the samples were subjected to load increments of $1/4$ and $1/2$ tons per square foot the treated sample consolidation in a much shorter period of time than did the untreated one. However, when the samples were subjected to load increments of 1, 2 and 4 tons per square foot the consolidation times for the treated and untreated samples were almost the same. Several instances occurred when the treated sample took longer to consolidate than did the untreated one. The reason for this abnormality is not known.

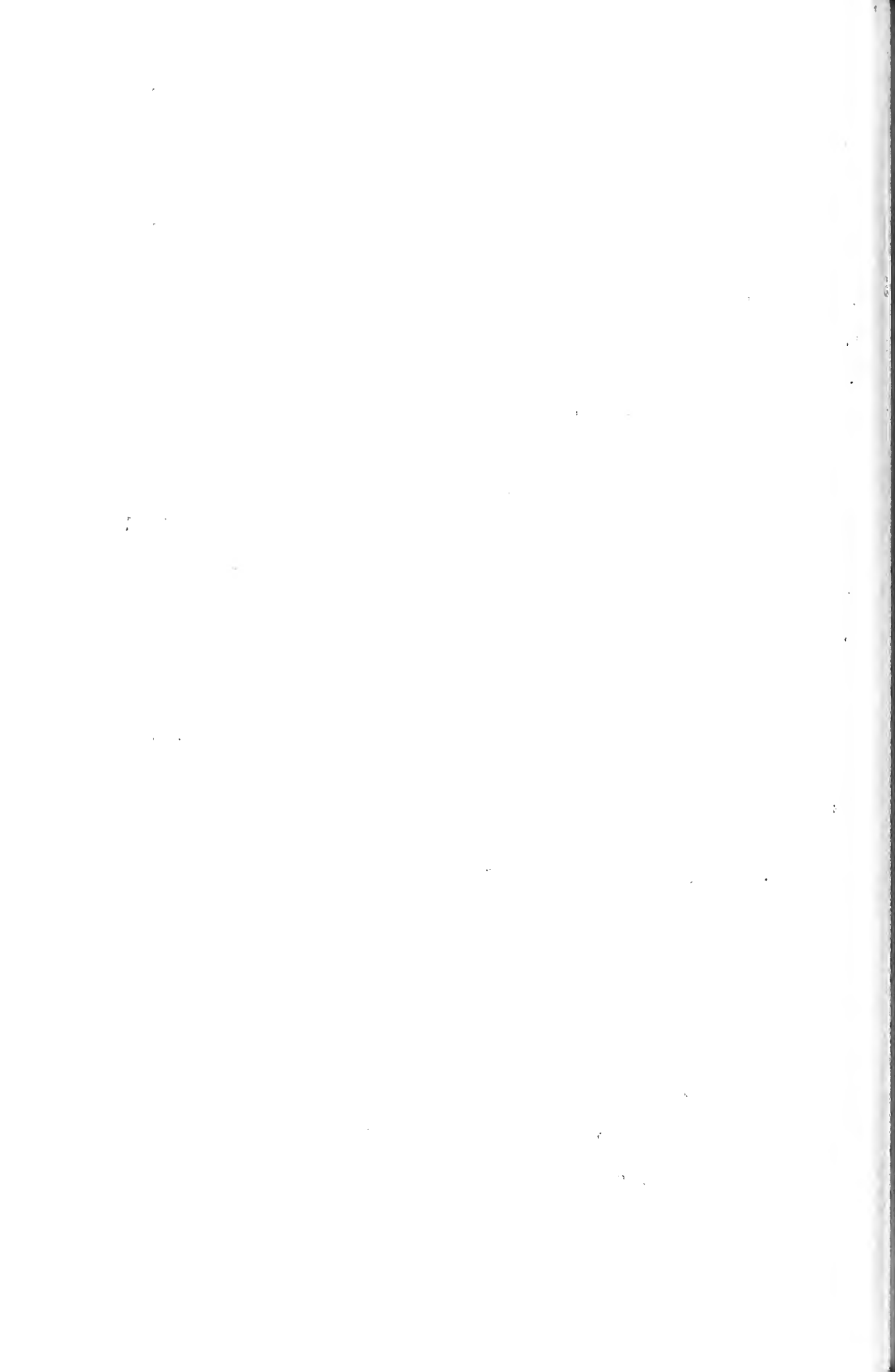
PART VI
CONCLUSIONS

After a careful consideration of the results obtained from this investigation and the literature studied, the conclusions indicated below were derived. This research should be considered only as a preliminary investigation and accordingly the conclusions derived therefrom should be applied with liberal use of good judgement. There are many facets involved in an investigation of the effect of electro-osmosis on the consolidation characteristics of a particular soil sample that must be thoroughly studied before meaningful conclusions can be reached. Time limitations permitted the author to investigate only those general effects indicated below. The author's conclusions are:-

(1) The electro-osmometer as designed and constructed meets the required functional objectives and is considered a success.

(2) The passage of a direct electric current through an illite-water mixture changes the physical properties of the sample near the cathode. The appearance of this portion of the sample indicates a definite trend of the soil to assume a new structure.

(3) The application of an electrical potential to an illite-water mixture using nickel-silver electrodes causes the values of the liquid limit, plastic limit and



plasticity index of the soil to become higher than those obtained for an untreated illite.

(4) The passage of direct electric current through an illite-water mixture results in a higher void ratio at one hundred percent consolidation for a particular load increment than for that of an untreated sample subjected to the same load increment. There is good reason to believe that this factor is due to electro-chemical hardening.

(5) Electro-osmosis also effects the time that complete consolidation is reached in an illite sample. For the smaller load increments the treated sample consolidates much more rapidly than does the untreated samples. However, as the magnitude of the applied load increment and the duration of the application of the electrical potential increase, the time differential for complete consolidation between the treated and untreated sample diminishes. In some instances it was noted that the treated sample was requiring more time to reach complete consolidation than was required by the untreated sample.

(6) The duration of the electrical pre-treatment of an illite greatly effects the sample resistance to electrical current flow during the early portion of the test. In general these observations indicate that an increase in the pre-treatment period results in a more rapid development of near-maximum sample resistance to electrical current flow.

(7) If an electrical potential is applied to an

illite sample which has been completely consolidated, the sample will consolidate to a greater degree and will if subjected to electrical treatment long enough expand a small amount.

(8) Although the results obtained by using nickel-silver porous plates as the anode and cathode are considered entirely acceptable, it is believed that their use should be discontinued. There is considerable evidence that both metals ionize and participate in base exchange activity and because of this fact it is difficult to determine effects of the individual metals.

(9) The coefficient of consolidation in illites is greatly effected by the application of electrical potential. The effect is more pronounced when the sample is subjected to the lower load increments and shorter duration of the application of electric current in that the displacement between the curves for the treated and untreated samples is greatest under these conditions.

(10) Since the observed temperature differentials between the sample and room temperature were so small, it is believed that the effect of this factor on the consolidation process can be considered insignificant when utilizing very low voltages.

PART VII
RECOMMENDATIONS

It is the author's opinion that the effects of electro-chemical hardening which accompanies the electro-osmotic phenomenon is a very important factor. Very little is known about quantitative or qualitative effects of electro-chemical hardening on clay-water mixtures. Further study is required to differentiate between the consolidation effects caused by electro-chemical hardening and those attributed to the evacuation of water from the soil sample and the establishment of pore water tension when an clay-water system is subjected to the electro-osmotic process.

One of the most important requirements needed to sustain the investigation into the effects of electro-osmosis at this school is a means of obtaining a variable voltage source. Although quite expensive, apparatus is marketed by commercial firms to convert alternating current to direct current and is so constructed that variations in voltage of 0-100 volts can be available. With this highly desirable electrical source research could be conducted on various soils to determine the economical amount of electrical current required in the practical application of the theory of electro-osmosis.

Variable voltage would also be a very necessary factor in determining the effect that temperature increases, resulting from the resistance the soil provides against the

flow of electric current, would have on the consolidation of soils by use of electro-osmosis.

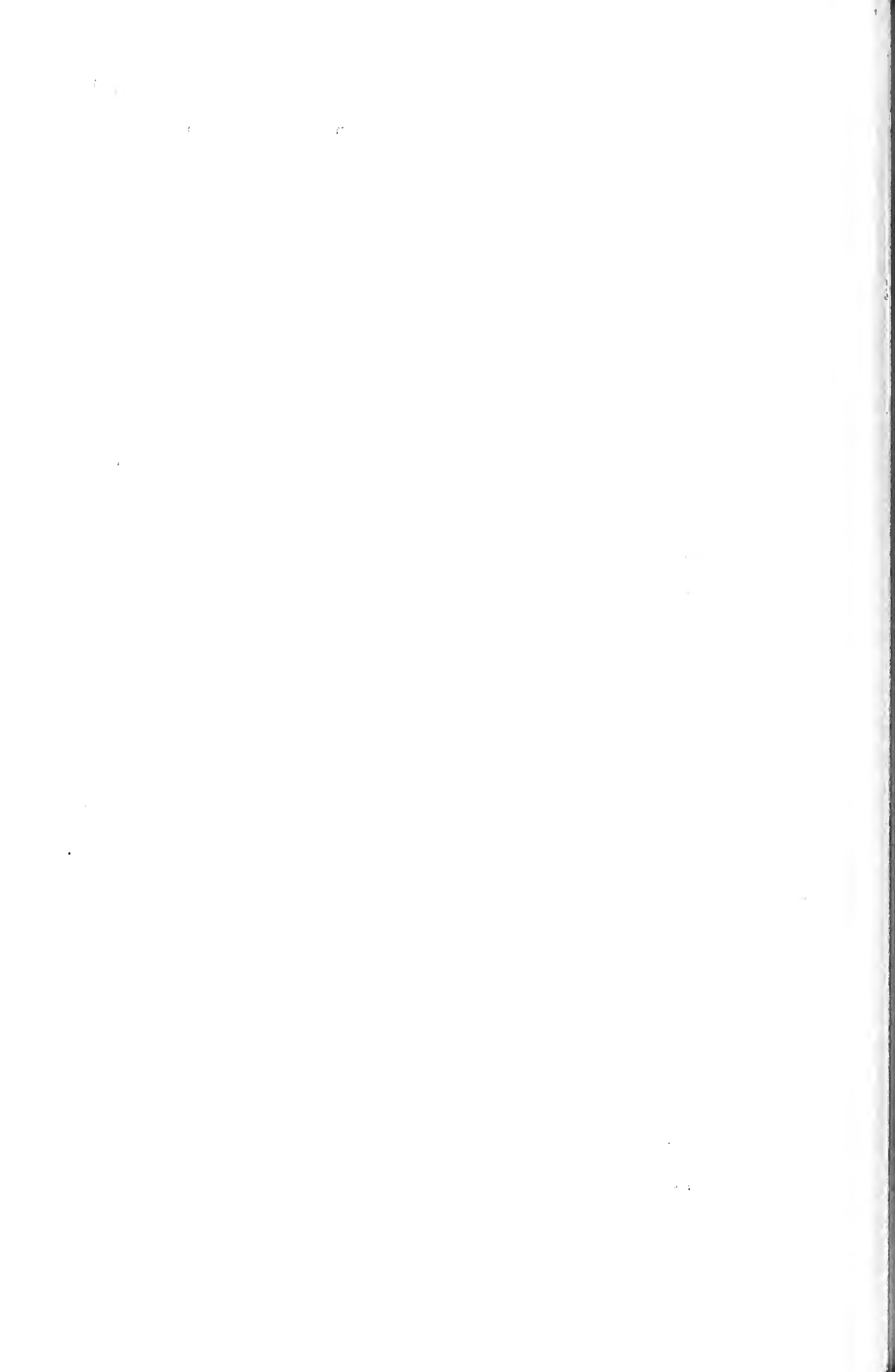
Several necessary changes in apparatus and test procedure were manifest during the series of tests conducted by the author. These changes are:

(1) In order to reduce the complexity of the base exchange evaluation, only homoionic clays should be used in testing. Of course, many types of ions should be used to saturate the various clay samples, investigated in order to determine the effect each particular ion will have on the electro-osmotic process. For comparison purposes, the results obtained from a natural sample would also be desirable.

(2) The porous material used for the anode and cathode plates should be composed of only one metal, preferably aluminum.

(3) Aluminum wiring should be used in the portion of the electrical circuit that enters the electro-osmometer. The wiring should be secured to the anode plate with an aluminum mechanical fastener. The purpose of this recommendation is to decrease the number of different ions introduced into the sample by electrolytic decomposition of the anode plate and the circuit wiring and its fastener.

(4) The anode plate should be carefully weighed after each test to determine its loss of weight. A complete chemical analysis should be conducted on the soil before and



after electrical treatment to determine the character of the base exchange activity occurring and the nature of the foreign material that is being introduced into the sample. It would also be helpful to have a chemical analysis conducted on the liquid on both sides of the sample in the electro-osmometer after each test series is completed.

(5) The mounting for the elliptical track, self return bushing should be modified so that the bearing could be removed without the necessity of removing the entire mounting. This modification would be especially valuable when attempting to remove the air pockets from the assembled apparatus.

(6) As indicated before the "O" ring gaskets for the end plate should be discarded and a new gaskets should be fabricated. The gasket should cover the entire area of the collar and should be composed of a rather firm rubber about 1/4 inch thick.

(7) The use of the rubber washers on the end plate bolts should be eliminated. Although they do eliminate damage to the lucite collars and end plates, they cause considerable binding in the bolt threads. Obviously, this causes great difficulty in the disassembly of the apparatus.

(8) Until more is known about the fundamental effects of electro-osmosis, it is believed that the application of electrical potential prior to loading should be eliminated.

(9) Although difficult to accomplish with a full classroom schedule, the duration of application of electrical potential for each load increment should be the same in each series of tests. This is necessary for purposes of easy comparison of results.

Ostensibly, there are a myriad of changes in procedure used in this series of tests that could be made to determine the effects of electro-osmosis on the consolidation characteristics of a soil sample. These changes will, of course, depend on the particular phase of electro-osmosis being investigated and the good judgement of the investigator.

PART VIII.

BIBLIOGRAPHY

1. Baver, L.D. "Soil Physics". New York: John Wiley and Sons, Inc., 1948.
2. Bernatzik, W. "Contribution to the Problem of the Seepage Pressure in Electro-osmosis". Proceedings of the Second International Conference on Soil Mechanics. Vol.VII, 1948.
3. Casagrande, L. "Structures Produced in Clays by Electric Potential and Their Relation to Natural Structures". Nature, London. Vol.160, 1947.
4. Casagrande, L. "Electro-Osmotic Stabilization of Soils". Cambridge, Mass., Harvard Soil Mechanics Series, 1952.
5. Casagrande, L. "Review of Past and Current Work on Electro-Osmotic Stabilization of Soils". Cambridge, Mass., Harvard Soil Mechanics Series, 1953.
6. Dawson, R.F. and McDonald, R.W. "Some Effects of Electric Current on the Consolidation Characteristics of a Soil". Proceedings of the Second International Conference on Soil Mechanics. Vol. V, 1948.
7. Endell, K. and Hoffman, V. "Electro-chemical Hardening of Clay Soil". Proceedings of the International Conference on Soil Mechanics and Foundation Engineering. Harvard University Vol.I, 1936.
8. Geuze, E.C.W.A., de Bruyn, C.M.A. and Jostra, K. "Results of Laboratory Investigation on the Electrical Treatment of Soils". Proceedings of the International Conference on Soil Mechanics. Vol.III, 1948.
9. Karpoff, K.P. "Stabilization of Fine-Grained Soils by Electro-osmotic and Electro-chemical Methods". Proceedings of the Highway Research Board. Vol.32, 1953.
10. Koonce, S.J. "A Study of the Soil Properties Important in the Application of Electro-osmosis". Troy, New York. Master's Thesis. R.P.I., 1954.



11. Preece, Edmund F. "Geotechnics and Geotechnical Research". Proceedings Highway Research Board. Vol.27, 1947.
12. Richardson, H.W. "Electric Curtain Stabilizes Wet Ground for Deep Excavation". New York. Reprint from Construction Methods and Equipment, 1953.
13. Schaad, W. "Electrical Treatment of Soils". Proceedings of the Second International Conference on Soil Mechanics. Vol.VI, 1948.
14. Shukla, N.P. "Electro-chemical Treatment of Clay". Third International Conference on Soil Mechanics and Foundation Engineering. Vol.III, 1948.
15. Spangler, M.G. and King, H.L. "Electrical Hardening of Clays Adjacent to Aluminum Friction Piles". Proceedings Highway Research Board. Vol.29, 1949.
16. Storch, H. "An Investigation of the Effects of Voids-Ratio on the Thermal Conductivity of Sand". Troy, New York. Master's Thesis. R.P.I., 1949.
17. Taylor, D.W. "Fundamentals of Soil Mechanics". New York: John Wiley and Sons,
18. Vey, E. "The Mechanics of Soil Consolidation by Electro-osmosis". Proceedings Highway Research Board. Vol.29, 1949.
19. Winterkorn, Hans F. "Fundamental Similarities Between Electro-osmotic and Thermo-osmotic Pressure". Proceedings Highway Research Board. Vol.27, 1947.
20. Winterkorn, Hans F. and Moorman, Robert B. "A Study of Changes in Physical Properties of Putnam Soil Induced by Ionic Substitution". Proceedings Highway Research Board. Vol.21, 1941.
21. Preliminary Reports, Reference Clay Minerals, Research Project 49, American Petroleum Institute, Jan. 1951.

Thesis
T16

33133

Tarran

An investigation on the effects of electro-osmosis on the consolidation characteristics of illite.

Thesis
T16

33133

Tarran

An investigation on the effects of electro-osmosis on the consolidation characteristics of illite.

thesT16

An investigation on the effects of Elect



3 2768 002 05470 2

DUDLEY KNOX LIBRARY